Analysis and Visualization of Traffic Signal Performances

Chenlu Wang

UNIVERSITY OF TAMPERE
School of Information Sciences
Software Development
Supervisor: Jyrki Nummenmaa
June 2016

University of Tampere
School of Information Sciences
Wang, Chenlu: Analysis and visualization of traffic signal performances
Master's thesis, 42 pages, 5 index pages
Software Development
June 2016

Abstract

Road transportation network is significant backbone of current society with the increasing demand of mobility. Traffic controlling is a big challenge in many cities, especially growing cities. Since the capacity of traffic throughput is limited in urban area, it is critical to improve the capacity of traffic network. Traffic signals controlling as an elementary component of all the road transportation system, and it is used to solve this problem of traffic conflict on intersections.

However, many traffic management systems lack the ability to qualify characterized arterial performances. That also provides the reason to develop methods to qualifying arterial performances. The performance of traffic flow through intersections depends on the phases, sequence and the timing of traffic signals. Therefore, efficient traffic signal operation is vital for smooth traffic flows in signalized network, and well-maintained signal operation is greatly beneficial for road users. With the increasing traffic jam on the road, traffic engineers are looking for some new approaches on intuitive interface to manage and analyze the traffic signal system.

Some traffic solutions provide measurements of traffic performance, like ImFlow system, which is a business product on European market. ImFlow requires very high expenditures for equipment, installation and maintenance. The purpose of my thesis is to develop a substitute of ImFlow that has no extra demand of equipment on roadway, as an economic and lightweight solution to satisfy the demand of performance analysis, and further to assist traffic engineers manage and maintain traffic signal system in prevailing intersections.

A critical work for the thesis is to select suitable and useful measurements of signal performances based on available traffic data and engineers' requirements. The selected performances in the thesis include green duration, queue length, waiting time, volume, maximum capacity, saturation flow rate, active green and percentage of vehicle arrival on green. The algorithms used in the thesis are referred from others' previous research and adjusted based on our actual cases. According to measurements of those traffic performances, traffic engineers could make decisions with analytical traffic data.

The thesis provides approaches to process and analyze traffic signal data in Finland, implement and visualize measurements of traffic signal performances. An important contribution of the thesis is that provides an economical and lightweight solution to analyze traffic signal data and spreads the service to general intersections.

Key words analysis, visualization, traffic signal system, signal performance measure

Contents

List of Figures

List of Tables

1 Introduction

1.1 Background

Road transportation network is a significant backbone of current society with the increasing demanding for mobility. Several cities in Finland occupy traffic volume over 30,000 automobiles in average per day which is demonstrated in Figure 1.1 from Finnish transportation agency. However, traffic controlling and management is a big challenge in many cities, especially growing cities. Due to the capacity limitation of traffic throughput in urban area, it is critical to improve the efficiency of traffic network (Chanloha, Usaha, Chinrungrueng & Chaodit 2012). Traffic signal controlling, as an elementary component of all the road transportation system, is used to solve this problem of traffic conflict on intersections by time division multiplexing (Aljaafreh & Al Oudat 2014).

Although the analysis of traffic performance on freeway in real time and based on historical data has been successfully achieved, the characterized arterial performance is still elusive. Furthermore, many traffic management and traveler information systems are lacking of that kind of ability (Wolfe, Monsere, Koonce & Bertini 2007). Therefore, it is quite meaningful to develop methods for quantifying arterial performance.

The performance of traffic flow through intersections depends on the phases, sequence and the timing of traffic signals. Therefore, efficient traffic signal operation is vital for smooth traffic flows in signalized network, and well-maintained signal operation is greatly beneficial for road users. With the increasing traffic jam on the road, traffic engineers are looking for new approaches on intuitive interface to manage and analyze the traffic signal system.

1.2 A statement of the problem

In general, smart traffic controller systems aim to improve the efficiency of traffic control and save time for all drivers, and to make traffic safe for pedestrians. Therefore, it is quite important to know how the systems work.

A traffic control unit records data from signals and detectors at intersections, and the data can be collected from controllers. Unfortunately, most existing signal control systems do not make it convenient to monitor or archive traffic signal performance data. During the thesis, we will develop a signal data analysis application. Hence, the analysis tools which could analyze the raw data to present concrete traffic signal controlling are appealing and necessary. In addition, they would tell the engineers if signal control system operates as designed.

On the other hand, general road users and stakeholders cannot access and analyze traffic signal raw data which usually is not open data. Sometimes there is a poor understanding of the relation between settings in use and their effects on operation.

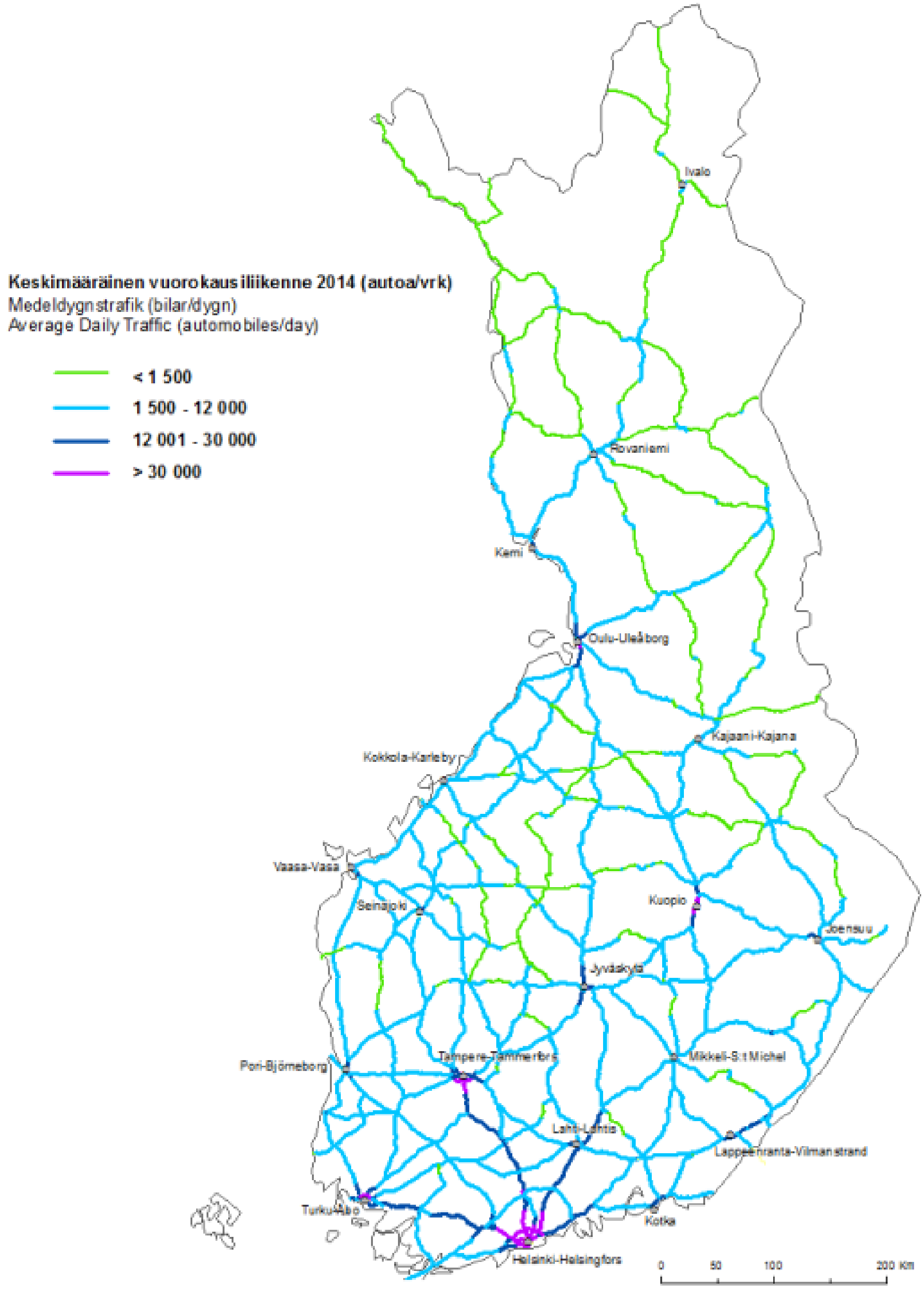


Figure 1.1. Daily volume of cities in Finland

Historically, many traffic engineers have made decision based on users' expectation and complaints, which is not a good practice (Koonce 2008). Based on the performance measured by an analytics application, users can easily gain comprehensive decision making help and look over the traffic condition without any programming or statistics background. With the analysis application, it is quite helpful for operators to build a context sensitive approach with consideration of the environment of traffic signals, location conditions and unintended consequences of potential changes (Koonce 2008).

Signal timing is complicated because operators cannot have a clear vision to insight the ongoing behaviors of the entire traffic signal system. Traffic signal operation is more complex than freeway operation, because it is difficult to identify the effects of any changes to the system without infrastructure to measure performances (Koonce 2008).

There are some traffic solutions providing performance. ImFlow is one of the products on market from the company Imtech Traffic & Infra, offering understandable policies and constraints to traffic engineers who need to setup and maintain the ImFlow system. The policies and constraints are directly entered into the system and can be used by adaptive algorithms to optimize the signal timing in real-time and also collect some historical data. ImFlow central is a web-based system for monitoring and controlling of DAAP devices. According to ImFlow central, users can interact with ImFlow using a web browser, configure tools and display setting for the best performance. The performance reports are available, which include signal performance, PT Route performance and route travel performance. (Ljubisic 2014)

However, due to the high requirements, expenditures for equipping hardware of ImFlow and other reasons, only a few intersections are deployed with Imflow system in Finland. For example in the city of Tampere, currently ImFlow is installed in only ten intersections on Satakunannkatu and Hämeenpuisto. As for the rest of hundreds intersections in Tampere, no specialized service about traffic performance measurements and analysis is provided to traffic engineers.

Therefore, it is necessary to develop a substitute that has no extra demand of equipment on roadway, as an economic and lightweight solution to satisfy the demand of performance analysis, and further to assist traffic engineers to manage and maintain traffic signal system in prevailing intersections.

The aim of this thesis work is to provide understandable information to traffic engineers in prevailing intersections to present the behavior of traffic signal controllers, evaluating the performance of smart traffic system and integrate the various analysis models into a interactive web service for multi-dimensional measurements and continuous monitoring of traffic performance. The analysis service is given the name ImAnalyst as a product of Imtech Traffic & Infra Oy.

1.3 The definition of terms

This application to be developed involves a lot of terminology about traffic signal regulations and road rules. The relevant terminology with definitions and brief explanations are listed alphabetically below.

`Actuated operation` All the traffic signal controlling operations are actuated from the vehicle detectors.

`Approach` A set of lanes at an intersection that accommodates all left-turn, through, and right-turn movements from a given direction (HCM 2010).

`Arrival rate` The mean of a statistical distribution of vehicles arriving at a point or uniform segment of a lane or roadway (Koonce 2008).

`Arterial` A signalized street that primarily serves through traffic and that secondarily provides access to abutting properties with signals (HCM 2010).

`Capacity` The maximum number of vehicles can pass over a specified roadway or section of roadway expectedly in a direction, during a certain time period.

`Critical lane group` The groups of lanes that have the highest flow ratio for certain signal phase (HCM 2010).

`Critical volume` A volume with the largest utilization of capacity on a road. It measures the number of vehicle passing over per hour per lane.

`Cycle` One complete sequence of the indication of traffic signals. Cycle time or cycle length is the time taken one cycle. The cycle length controls the time from one intersection green to the next intersection green. It is often pre-set by the particular plan used.

`Detector` The sensing equipment that requests or extends on a specified traffic and pedestrian phase. It includes the loops buried or above the carriageway and some other kind of detectors.

`DINT` The code representing the status of detectors used in the traffic flow garner system.

`Downstream` The direction of traffic flow (Koonce 2008).

`Flow rate` The equivalent hourly rate at which vehicles, bicycles or persons pass a point on a lane, roadway or other traffic way; computed as the number of vehicle, bicycles or persons passing the point, divided by the time interval in which they pass.

`Gap, extension or passage time` Passage time determines the extendable part of the green timing for a movement. As an example, assume the passage time is 3 second, and no vehicles pass after 3 seconds, then the movement should terminate (Wikipedia 2015).

`GRINT` The code presenting status of signal group using in the traffic flow garner system.

`Headway` The time in seconds between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (Koonce 2008).

`Intergreen period` The time between end of a green phase and start of the next green phase for another. These comprise of several seconds amber for the phase losing right of way and several second amber/red for the phase gaining right of way. The all red might occur to allow clearance depending on the geometry of the intersection.

`Loop detector` The inductive loops embedded on the road surface relying on the electromagnetic change to detect vehicles passing over.

`Maximum green` The maximum duration of a green signal after a conflicting demand has been registered in the controller.

`Minimum green` The minimum green during green signal time with no change of the signal lights.

`Movement` Movement describes the user type (vehicle or pedestrian) and action (turning movement) taken at an intersection. Two different types of movements include those that have the right of way and those that must yield consistent with the rules of the road or the uniform vehicle code (HCM 2010).

`Offset` The time difference between a certain point in a cycle and a reference point at an intersection.

`Passenger car unit` A unit for measure the number of vehicles consideration the large trucks and turning movements using multiplication factors. It allows you to handle mix traffic streams more accurately than just assuming all the vehicles are same.

`Peak hour` The hour of a day that obverses the largest utilization of capacity or when there is largest number of vehicles uses the traffic approach or lanes.

`Pedestrian crossing time` Pedestrian crossing time serves on the green time allocated to each phase of a cycle. It is the sum of green interval and inter-green interval.

`Platoon` A group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily because of signal control, road geometry or other factors (HCM 2010).

`Pre-timing operation` All the traffic signal operations follow a fixed sequence, signal cycles with fixed length.

`Queue` A closing space collection of vehicles nearby intersection stop bar.

`Queue discharge` A flow with high density and low speed, in which queued vehicles start to disperse (Koonce 2008).

`Right of way` The right to move for a traffic movement in a particular direction.

`Saturation flow` The maximum flow during the green time from discharging queue. It is usually indicated by vehicle or passenger car unit per hour.

`Semi-actuated operation` The intersection is programmed to operate a fixed time every cycle, until there is a demand from some particular movements.

In addition, for understanding the research well, some other traffic conventions in Finland are needed to learn.

Firstly, as for data naming, names of intersections often are combined with a prefix standing for the city and an index number. For example, intersection “TRE306” starts with “TRE” means that it is the intersection number 306 located in the city of Tampere.

Secondly, names of signal groups are letters with the convention that the signals of pedestrians always start with an underscore, like _G, to distinguish from signals of vehicles.

Last but not least, since there are many different kinds of detectors with various significance, it is helpful to understand the type of a detector from its name. In general, inductive loops are the most common and widely-used detectors organized in different sizes and shapes, whose name is always starting with the upper case letter of signal group and a number meaning the distance between the detector and intersection stop bar, for instance, “B100” means that the detector belonging to the signal group B with 100-meter distance. In addition, “A60_1” and “A60_2” indicate that at the place located with 60-meter distance from the stop line, there are two paralleled detectors on the two lanes under the controlling of signal A.

1.4 Technical background

The development procedure of the entire system as illustrated in Figure 1.2, which is mainly divided into three steps, simply summarized as: traffic signals data collection, storage and analysis. The research work of this thesis focuses on the last part: analysis and visualization of traffic signal performances. A practical scenario is that traffic engineers send analytical requests via web browsers to the server, and data retrieved from database using the parameters on users' submission, then the computation is processed on the back end of the server. After this, the analysis results will return to users and are rendered on the web interface in a proper way.

The prerequisite step to achieve the goal of research is obtaining data. As it is illustrated in the first block of Figure 1.2, once any status of signal group and detectors updates, the data collection unit of local controlling gets the message. According to a serial port communication, these messages are synchronous and provide consistent data flow to the data garner system. After this, the TrafficFlowGarner system is used to handle the incoming data by itself and store it into database. The core development techniques will consist of the following main components:

Production components

- Python: The traffic signal analysis application called ImAnalyst is implemented as an interactive web application using Django web framework written in python.
- Django: Django is a free and open source framework following model-view-controller (MVC) architecture, encouraging rapid development and clean, prag-

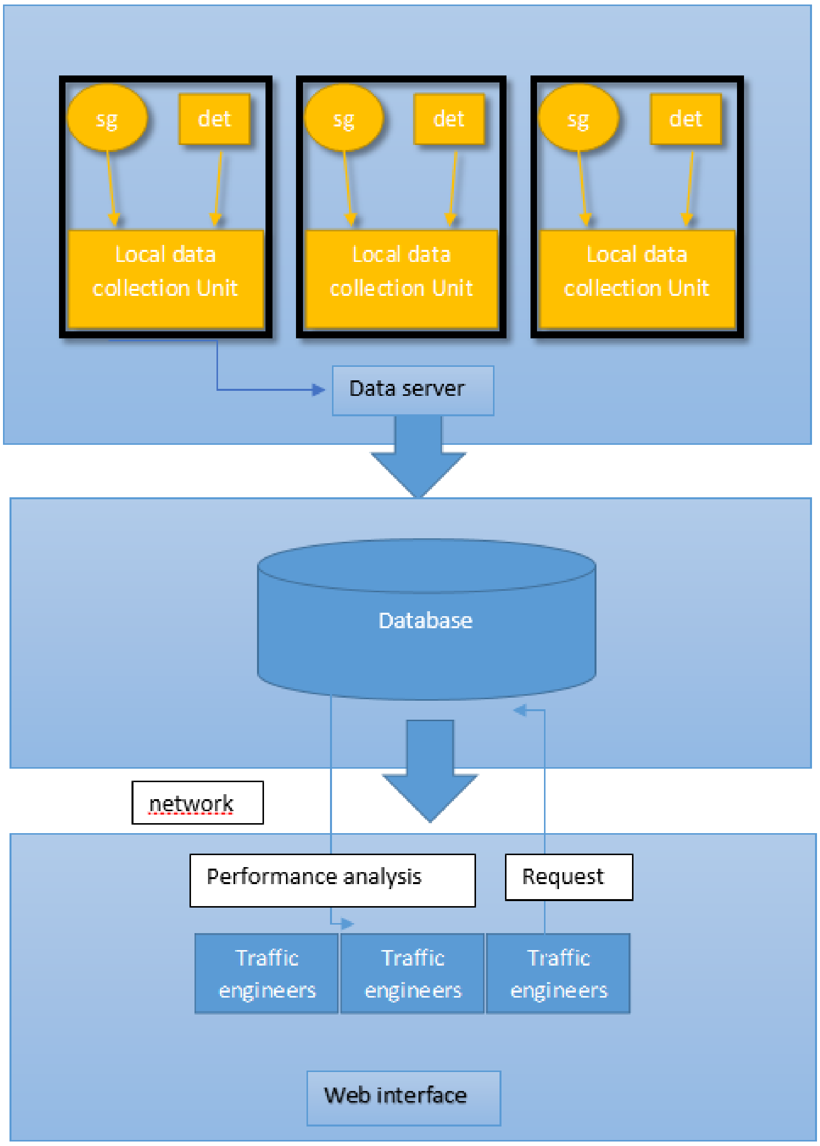


Figure 1.2. System flow chart

matic design.

- PostgreSQL: PostgreSQL is the supported database of this production as it is used by TrafficFlowGarner system as well. It is an object-relational open-sourced database management system to store data securely, supporting very good practice and allowing the retrieval at the request from other software applications.
- Git: Git is used as the version control system of the project during development.

User interface components

- Template: Django templates contain the static parts of the desired HTML, and the dynamic content can be inserted into the templates with some special syntax in Django template language.
- Static assets: Within the template, static files are referred to as template tags. The system uses CSS, JQuery and JQuery assisted UI components to build HTML.
- Bootstrap: Bootstrap is a twitter-style web framework.

Development components

- Anaconda: Python distribution that has to have almost all required packages in one. Due to the huge demand of data processing and analysis, Anaconda environment is used for simplifying package management. It is a python distribution having almost all the required packages for large scale data processing, analytics and scientific computing.
- LiClipse: Lightweight editors for Python development. It is possible to use other IDE as well.

Key parts

- Middleware: Authentication of the project is controlled by a common middleware component. Only the users whose IP addresses are included in the allowed IP range of network can access the application. The allowed network set is defined in the settings file.
- Django session: Django session provides a "per-site-user" solution. Request session is used to pass values between different views. However, it must be ensured that 'SessionMiddleware' is activated. In addition, GET requests and POST requests also pass values in views.
- User permission: Users' identification and authentication are performed in the middleware, which decides whether a user is able to access the application or not. The range of intersections that users could access is specified. The mapping of IP address and intersection naming is also defined in setting file.
- Database: The system connects to the database of traffic flow garner system. Traffic flow garner system is used to collect and store traffic signal controlling data into database. The configuration of database connection is done in the settings file of the project. To retrieve data, the system handles database using raw SQL queries in Python code. Another way to access database is by Django models.

1.5 Thesis organization

The next of thesis is separated into the following chapters:

2. Fundamentals of traffic signal controlling
3. Analysis and visualization of traffic signal performances
4. Validation and evaluation of traffic signal analysis
5. Discussion and conclusion

Each of the chapters treats into several aspects, many of which are discussed in more than one sections. In Chapter 2, the basic operation principle of traffic signal controlling is introduced and some previous work and related algorithms are mentioned. The original work are presented in Chapter 3, then evaluation of reliability and accuracy of those measurements is evaluated in Chapter 4. Finally, discussion and conclusion are in the last chapter.

2 Fundamental and theory of traffic signal controlling

Traffic signals provide orderly and safe traffic movements at intersections, reduce the travel timing of vehicles passing through the intersections and balance the efficiency of management to all the traffic flows (Traffic signal wikibook 2015). In an ideal condition, the signal control system should allow all the vehicles passing without stops, that means, phase transitions organize a green band through all the intersections for each vehicle from the starting point to the destination. Such control system is in fact impossible to implement.

In general, the common signal control system consists of three types: the pre-defined type with fixed phases, vehicle actuated type which totally depends on the demand of vehicles and semi-actuated ones (List & Cetin 2004). The intersections equipped with detectors are called ”actuated”. Furthermore, an intersection with all approaches actuated is called full actuated and an intersection without detectors is called non-actuated or fixed. For saving money on maintenance, some intersections are set as semi-actuated (Wikipedia 2015).

2.1 Signal timing operation

Wikipedia (2015) defines signal timing as the technique that traffic engineers used to determine the right of way at intersections, the duration of green for vehicles and pedestrian walk, and many other related factors. In addition, cycle length is defined as the time from one main street to the next main street for coordination.

As United States Department Transportation (2015) suggests, all the signals that are synchronized together must operate the same cycle timing. Generally, the longest cycle length demand would be used. However, if there are three synchronized intersections requesting 75,80 and 80 seconds cycle length respectively, the 80-second cycle length should be operated. In a word, a common cycle length is significant to operate coordinated signals. The classical approach to determine cycle length provided by Webster, F. V. (1958) is expressed in the equation

$$C = (1.5 \times L) \div (1.0 - Y_i), \tag{2.1}$$

where C is optimum cycle length in seconds, and cycle lengths in the range of $0.75C$ to $1.5C$ do not increase much delay, L represents the lost timing per cycle in seconds and Y_i is sum of the saturation degree for critical phases (United States Department Transportation 2015).

2.2 Study of queue at intersections

Two typical and primary measures of performance of intersection are queue length and delays, with associated with frequent stops caused at intersections. The queue length is a good quantification for the performance of an intersection. The number of vehicles in the queue and associated delay is worthy to be calculated for improving and inspecting the traffic management strategies (Anusha, Vanajakshi & Sharma 2013).

Estimation of queue length is a long-standing issue. The traditional approach is to handle it by input-output traffic flow, which works well with the queues shorter than the distance from the selected detector to intersection stop line (Liu, Wu, Ma & Hu 2009). Another method is to use traffic shockwaves to calculate queues. As byproducts of traffic congestion and queueing, shockwave are traveling disturbance between two traffic states (Traffic wave wikipedia 2015).

The widely and commonly applied sensors are loop detectors in Finland for detecting vehicles automatically. The loop detectors will return a pulse when any vehicle pass over it. The value of digitalized pulse is higher than the pre-setting threshold of the detector when vehicle passed and ideally equals to zero when no vehicle passing on (Anusha et al. 2013). In reality due to existing noise, the pulse could be slightly higher than zero and sufficiently lower than the threshold.

Webster asserted a traditional method to estimate queue length at signalized-intersection, which is used to analyze the cumulative traffic input and output in his book Traffic Signal Settings (Liu et al. 2009). The Input-Output model is based on the difference between the total arrivals and the total departures, which has obviously drawbacks. Firstly, it could just handle queues that are shorter than the length between detectors and intersection stop line (Liu et al. 2009). Secondly, it is too dependent on the accuracy of traffic flow measurement. Last, it requires the initial number of vehicles which is hard to obtain from loop detectors (Anusha et al. 2013).

Skabardonis and Geroliminis (2008) designed an analytical model for real-time estimation along arterials, which compares the estimated travel times with simulated data to predict travel time on selected intersections.They proposed a method that uses aggregated loop detector data in 30-second time interval to estimate queue length at intersections.

Liu et al. (2009) created an algorithm using shockwave theory to estimate the queue length in intersection even when the road is congested with a queue which length is longer than the distance from intersection stop line to advance detector. This algorithm is relatively complex requiring to calculate multiple shockwaves and identify ”break points”, and their model utilizes the break points with high resolution. Finally, based on identification of the break points, to make a decision to select methods for event-based data, second-by-second data and wired detector data respectively. The approach asserted by Anusha et al. (2013) is suitable to estimate the queue length at intersections under low volume conditions. In their research, they observe the actual number of vehicles entering and exiting manually from a video. The accuracy of the approach to estimate queue length is shown in Figure 2.1 estimated by queue polygon method.

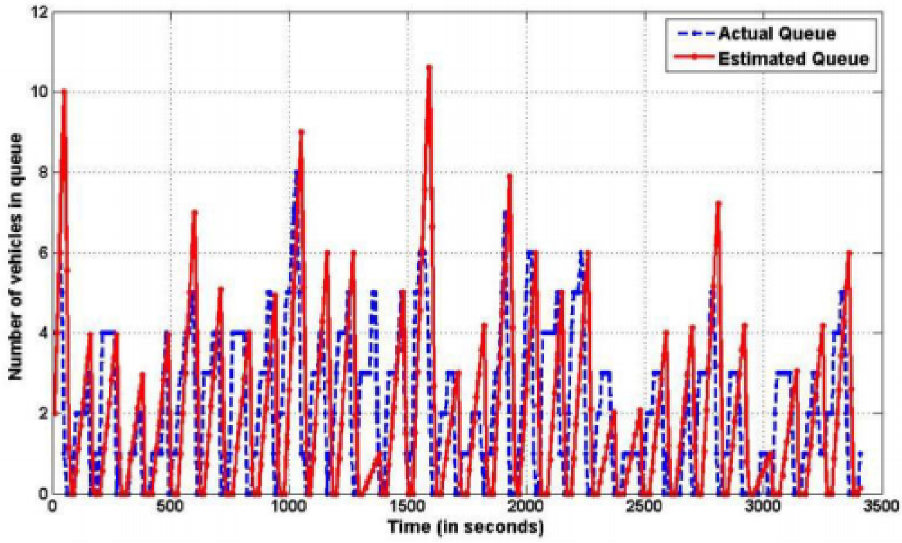


Figure 2.1. Queue estimated by the queue polygon method

The algorithm of queue polygon processes input such as exit detector actuations and signal timing information. At the end of every cycle the algorithm estimates the queue length for the previous cycle. The required signal timing information includes the cycle start time, end of red and end of green for every cycle. The key of the queue clearance time is figuring out a ”cut-off point”, when the queue actually gets clears. Thus, the vehicles, after the queue clearance timing, arriving the entrance detector can pass the intersection without delay and stops.

In the traffic analysis tool, the number of vehicles passing over specified intersection and detector in every cycle from the end of green time to the end of red time will be calculated.

2.3 Delay at signalized intersections

Vehicle delay is a very important roadway traffic metrics in evaluating the performance of traffic signal controllers. Delay at intersections is usually difficult to be determined because the arrival and departure process is non-deterministic, which might be caused by the existence of traffic signals, the signs and the crossing traffic (Ban, Herring, Hao & Bayen 2009).

However, there are many models using some assumption to simplify the complex issue. Delay can be estimated with the knowledge of arrival rate, departure rate and red timing. Delay at an intersection also can be approximately treated as all the extra time that a vehicle spends at the intersection comparing the time it should pass without any hindrance. The total delay includes deceleration delay, stopped delay and acceleration delay.

Ban et al. (2009) supposed a delay pattern to estimate the delay for any vehicle at any time of a day at the intersection. Most existing delay models need the knowledge of traffic signal timing and traffic volume to estimate intersection delays. However, their model does not require signal timing data, only some sample travel time between two consecutive location on the street between upstream and downstream of the intersection. The two-step algorithm is: firstly, as the delay curves are piecewise linear (PWL) curves, delay measurements can be fitted by linear models using a simple curve fitting algorithm. Secondly, the increase in delays right after the start of the red time is handled.

2.4 Research on saturation flow rate

Accurate saturation flow rate is a vital fundamental in urban traffic signal controlling management and design. Many factors lead to different saturation flows on the roads. Influence of those factors includes:

- A multitude of different kinds of vehicles on the road with different performances, such as buses, trucks and ambulance. The heavy vehicles may influence saturation flow rate decreasing in two ways: They keep longer headway and also increase headways of other passenger cars.
- Driver behavior varies based on personalities and traffic rules.
- Roadside activities like parking and non-transport activities which effect road condition.

Under ideal conditions, during the signal showing green, firstly there is a short gap as the first vehicles react to move, then the queue of vehicles could reach a state where the vehicles are passing the stop line one by one with a constant gap or headway. The last vehicles in the queue are supposed to be slow down at the end of green timing to red period (Turner & Harahap 1993). Thus, HCM (2010) suggests a way to estimate saturation flow rate by recording the time of passage of the fourth and tenth vehicles to determine the value based on the assumption that the initial queue at the end of previous red period is not less than ten vehicles.

The first and last few vehicles are excluded because they suffer from losing green time. In the thesis work, this approach proposed in Highway Capacity Manual was applied to calculate saturation flow rate. Due to queuing theory, the vehicles in a queue will discharge at the saturation flow rate and we can take advantage of the average headway of the vehicles and convert it to saturation flow rate. For instance, if the stable headway is two seconds per vehicle in average, in other words, every vehicle requires two seconds of the effective green, the saturation flow rate of this lane is 1800 vphgpl (vehicle per hour of green per lane).

For general calculation purpose, Greenshieds found that the first vehicle enters an intersection with 3.4 second delay, while subsequent vehicles take 2 to 2.5 seconds in average to pass over a detector when considering the headway between vehicles (Idaho Transportation Department 1995).

Turner and Harahap (1993) proposed several methods to collect saturation flow data for estimating saturation flow and using multiple linear regression to build predictive saturation flow models. The basic idea is to use timekeeper and record the number of vehicles in every 6-second interval as Method 1, where the start period sets to 10 seconds as Method 2 and one where the start period equals the time for three vehicles to depart is Method 3. Their conclusion is that Method 2 gives the most appropriate result.

Due to the traditional method might lead to underestimated results, Shao and Liu (2012) provide an approach to study stochastic nature of queue discharging headways and to develop a model to estimate the saturation flow rate based on the surveyed data set. They found that the queue discharging headway is fitted in lognormal distribution and its density function is

$$f_H(h) = \frac{1}{\sqrt{2\pi}\delta h} exp(-\frac{(lnh - u)^2}{2\delta^2}), h \geq 0. \tag{2.2}$$

The traditional way to calculate saturation flow rate is as

$$S = 3600 \times \frac{1}{h}. \tag{2.3}$$

Whereas, they proposed a new estimation of saturation flow rate to be

$$S = 3600 \times exp(-\frac{1}{n}\sum_{i}^{n} lnh_{si}), i = 1. \tag{2.4}$$

When the headway distribution is symmetrical, this development method is consistent with the traditional approach, otherwise, when the distribution is unsymmetrical, the traditional method will cause underestimation.

3 The methods to analyze and visualize traffic signal performances

This chapter focuses on presenting the visualized analysis of traffic performances based on the fundamental principles of transportation, which include signal timing, queue and delay analysis, traffic capacity estimation, volume counting and so on.

All of the study cases used come from ImAnalyst, the web application for traffic signal analysis. The user interface of the analysis page is illustrated in Figure 3.1. On the left sidebar, first there is a drop-down list of performances, users are free to select any performance to analyze and determine other relevant parameters based on their specified demands. The result of analysis will be shown on the right main panel, including the visualized graph and preview of calculated data. Download data as CSV files is also allowable.

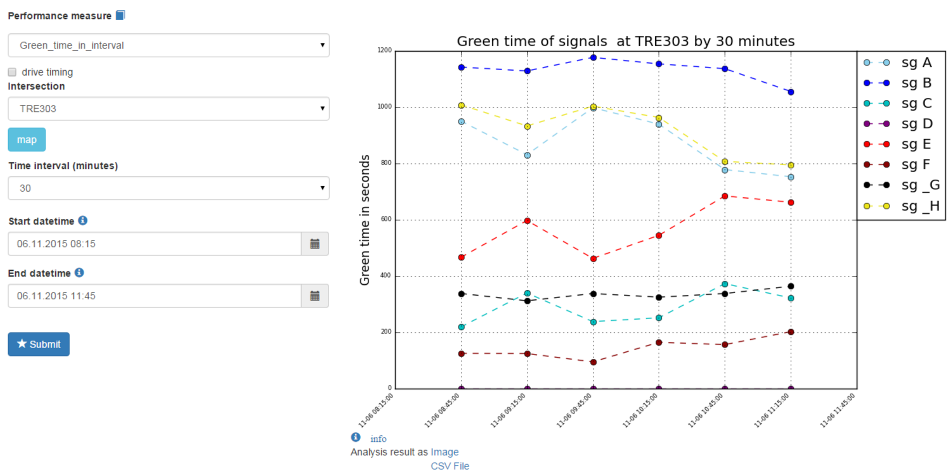


Figure 3.1. The user interface for analysis page of ImAnalysis

3.1 Signal timing

3.1.1 Green timing

Green duration is the time duration of a external state "green" sequence from a signal group. Acquisition of green timing helps traffic engineers to check if signal timings are operated as designed and try to achieve the allocation of green to every direction is optimal. There are three measurements about green duration from different facets, that means every green phase could be recorded in seconds and percentile per cycle. In addition, the total green duration in specified time period is also available.

Figure 3.2 demonstrates the green duration in the intersection TRE303 from 14:00 to 14:40 on 10th, July, 2015. The function calculates green duration per cycle.

Multi curve lines represent all the signals at the selected intersection. As to each single line, the y-value of the solid point means the time duration of a green phase in seconds and x-value of the points means the date and time when the green phase starts from.

During the selected time span, for the most time, signal group B takes up the longest green time, and the next are signal A and signal _H with identical variety, as the map of the intersection TRE303 (Figure 3.4) shown, both signal A and pedestrian signal _H control the direction from west towards east. Beside, the green timing of pedestrian signal _G is almost fixed at 13 seconds.

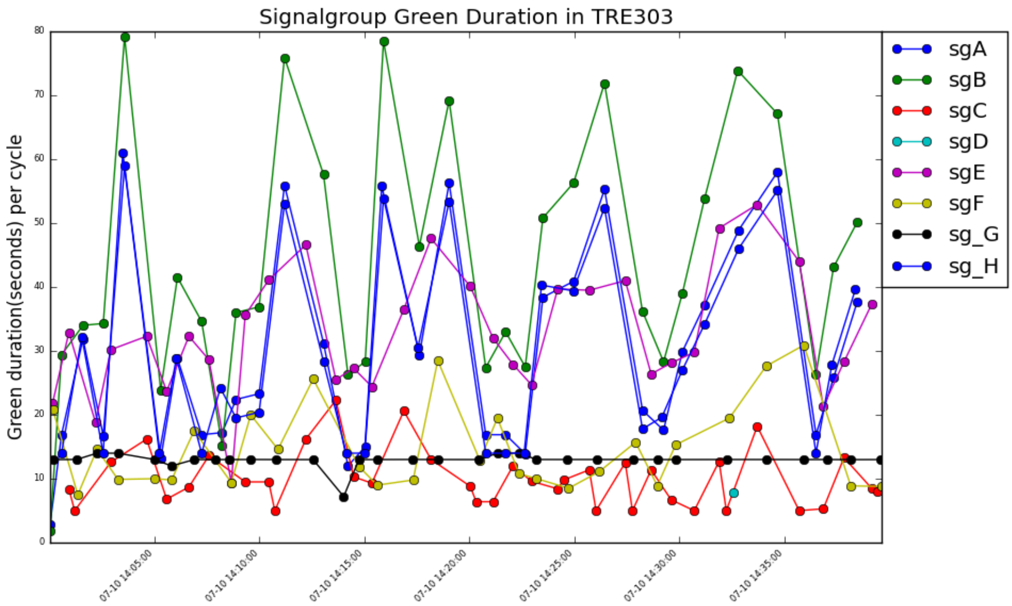


Figure 3.2. Green timing

Figure 3.3 indicates the proportion of green time in the cycle time, which proves that the trend of percentage of green in the whole sequence of green, amber and red phases. The curve lines are not same with the green timing in seconds, but the rank of green percent for signals keeps in pace with their green timings. Only the signal B always occupied over 50% percent.

Figure 3.4 shows the intersection TRE303 located at Satakunnakatu in Tampere, and tells the locations of signals and loop detectors. The movements controlled by signal A and signal B are critical movements, that is the reason that they occupied longer green times per cycle.

3.1.2 Active green

Active green is of importance to deduce efficiency of green timing. In general, the more timing active green takes in the whole green phase, the more efficient it indicts. That is especially useful for those directions holding longer green time at intersections. In other words, if there is always considerable passive green existing

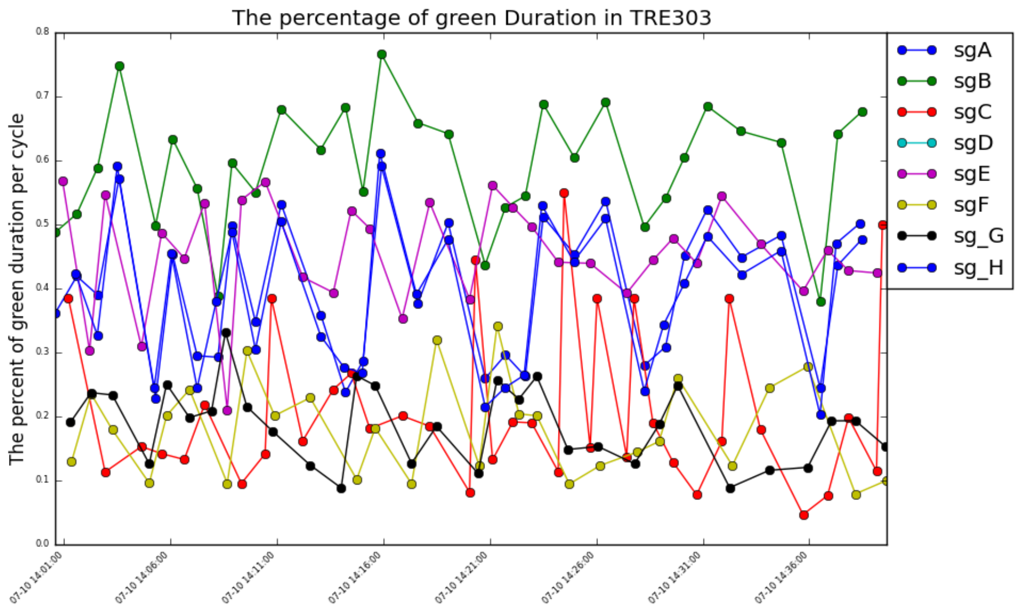


Figure 3.3. Percentage of green

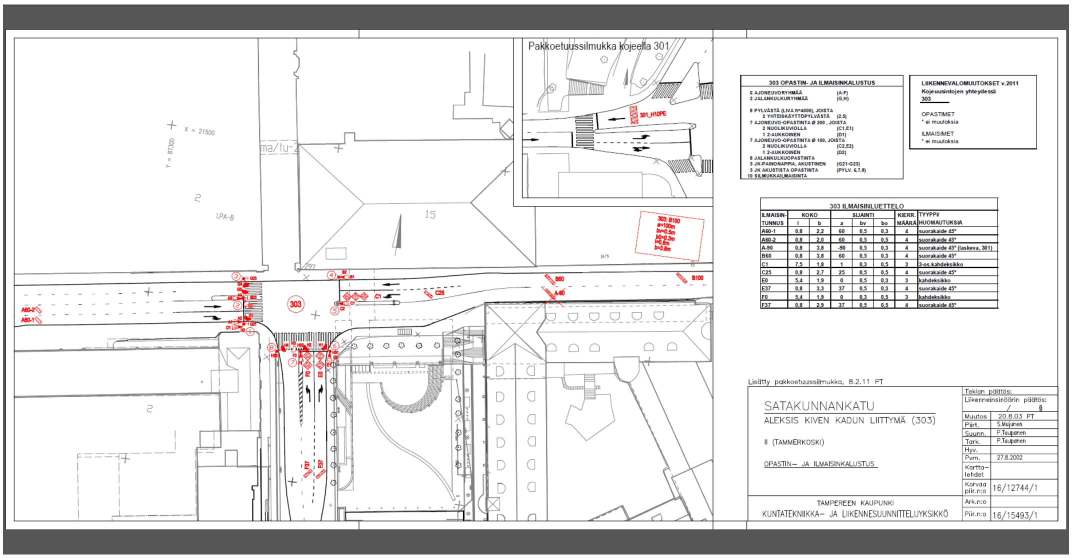


Figure 3.4. Map of intersection TRE303

on some way, traffic engineers might pay more attention to it and consider to enhance signal efficiency.

Based on the general knowledge, active green is the timing of a signal group from green start to the time when last vehicle comes. Oppositely, passive green is the timing after last vehicle comes until the end of green phase. However, from the internal state of signal group ("grint") recorded by traffic signal controller, the time of state "PASSIVE_GREEN" is counted, while the active green timing is left green excluding "PASSIVE_GREEN" during a green sequence. Hence, the calculation of active and passive green based on the two principles are implemented and compared.

The function calculates active green length per cycle of the selected signal, comparing its timing of passive green based on the two different definitions. The stacked bar chart in Figure 3.5 shows proportion of both active green and passive green. The x-axis is actual time of a day, and y axis is time duration in seconds.

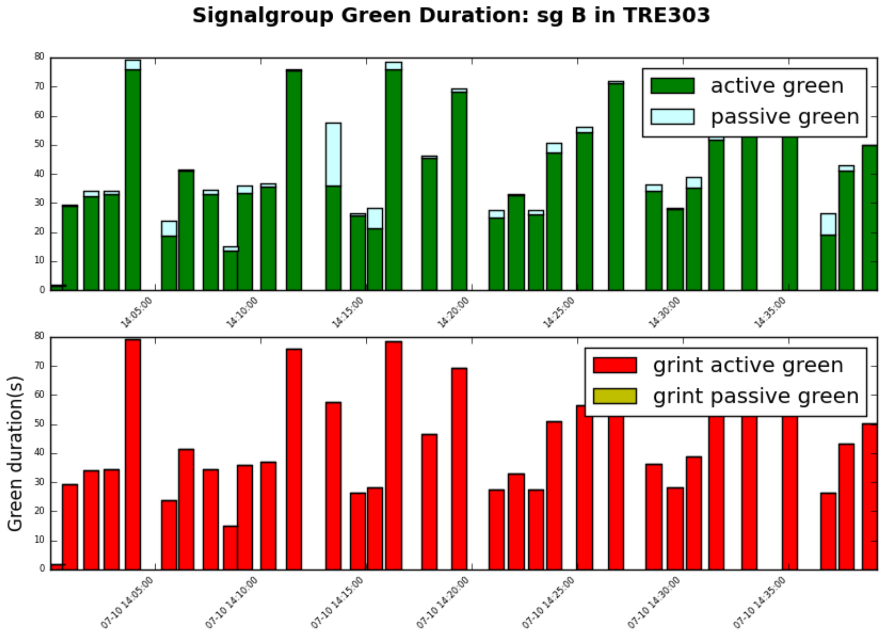


Figure 3.5. Active green

Figure 3.5 shows the result of this measure for signal group B at intersection TRE303 in Tampere from 14:00 to 14:40 on 10th, July, 2015.

The upper chart is visualized based on occupancy of this detector, every bar represents length of an entire green sequence. During active green (dark green), there are requests for vehicles received by any associated detector. Conversely, during passive green (light blue), it starts at the moment that last vehicles came and no detector is occupied at all, and ends this green phase. Signal B as the signal group which operates the longest green time in the intersection, little green is squandered when no vehicle is detected, though it could be absolutely active under ideal condition.

The lower chart shows the proportion of active and passive green based on “grint” state codes, the red part means “grint” active green timing. And the yellow part is for the time duration when the signal state is “PASSIVE_GREEN”. By comparison, the distribution of active green and passive green times are not corresponding with the upper bar chart. In the specified time span, there is no “PASSIVE_GREEN” at all.

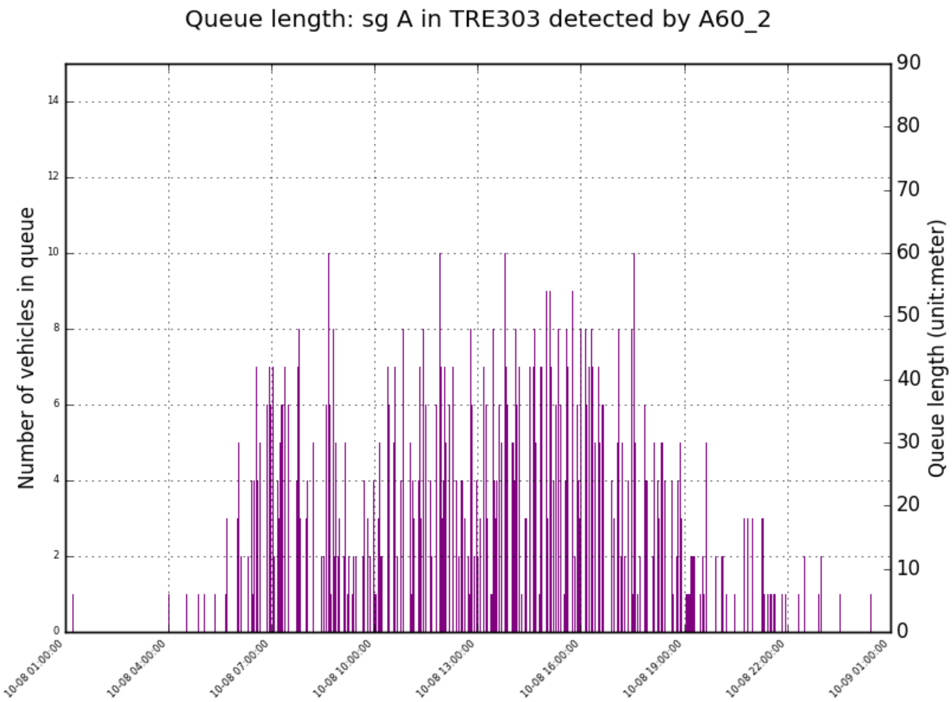


Figure 3.6. Queue

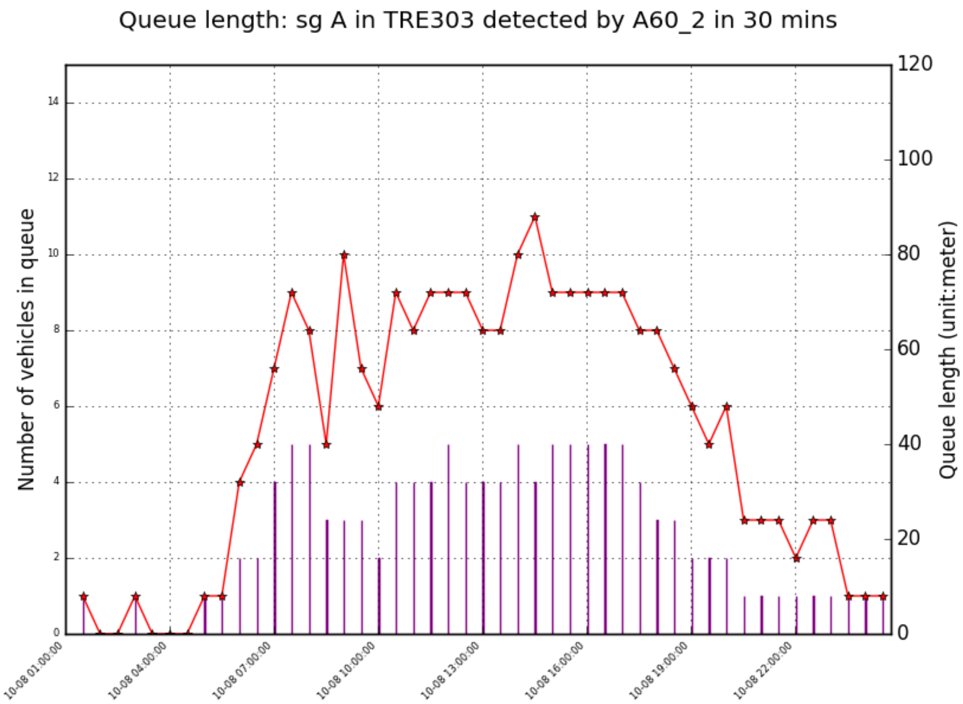


Figure 3.7. Average and maximum queue in every 30 minutes

3.2 Queue and delay at intersections

3.2.1 Queue length

At signalized intersections, queue length is the queue of vehicles at the end of red time (red-end) by lanes according to detectors. Queue length estimation is a pretty important intersection performance measurement. Efficient offset times should consider the time to discharge the queue at intersections, moreover, estimation of queue in next cycle is good for optimizing the entire signal system.

Traffic engineers can use queue analysis to identify problems and improve the efficiency of traffic signal control by maximizing traffic throughput at an intersection. Furthermore, calculation of queue could assist decision makers enhance the service from individual intersection to entire traffic network.

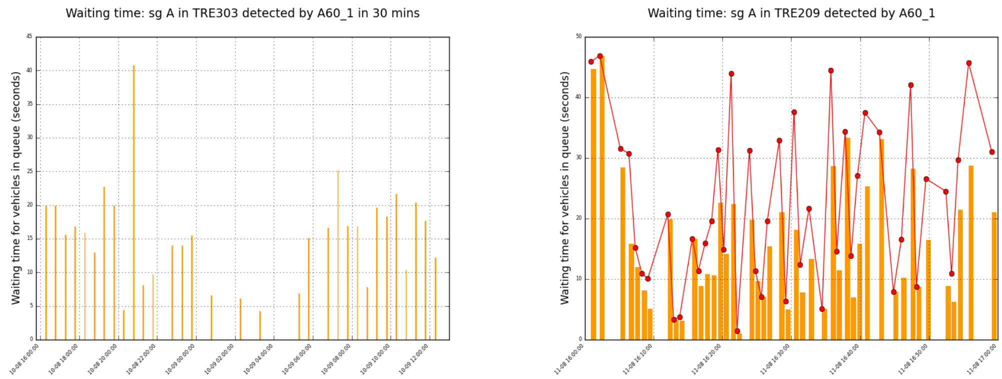
This measurement is used to estimate the length of stationary queue in meters and amount of vehicles forming a queue on the end of red time. The plot of this measurement has dual y-axis. The left y-axis is number of vehicles and right y-axis is length of queue in meters, while x-axis is actual time when red phase ends.

Figure 3.6 shows the result of queue length estimation via detector A60_2 under controlling of signal group A at intersection TRE303 in Tampere from 00:00 to 23:59 on Thursday, 8th, October, 2015. From midnight to 5:00, almost no vehicles went through and at about 6:00 in the morning, queues start to occur. Figure 3.7 illustrates average and maximum value of queue in every interval. The red curve line with asterisk symbol over the bars is combined by maximum queues and the bars are average queue in every half an hour.

3.2.2 Waiting time at intersections

Waiting time estimates the extra time vehicles in queues spend at intersections before moving from stop bar. Delay at an intersection also can be approximately treated as waiting time that a vehicle spends at the intersection comparing the time it should pass without any hindrance. The approach to calculate waiting time is related to queue length and headway of vehicles at intersections. The default value of headway is 2 seconds and distance between two successive vehicles as they pass a point on the roadway is 8 meters.

Figure 3.8 shows waiting time of vehicles at intersection TRE303 detected by detector A60_1. Figure 3.8(a) represents the estimation waiting time in average for every queued vehicle in every 30 minutes from 18:00, 8th of October to next day 13:00. Figure 3.8(b) calculates waiting time of vehicles in every queue. An orange bar is the mean of waiting time in this queue and a red dot is the maximum waiting time.



(a) Waiting time in time interval

(b) Waiting time in cycle

Figure 3.8. Waiting time

3.3 Traffic capacity

3.3.1 Saturation flow rate

Saturation flow rate is an elementary parameter to measure the traffic capacity and vehicle discharging time at intersections (Shao & Liu 2012). The saturation flow rate crossing a signalized stop line is defined as the number of vehicles per hour that are able to cross the line if the signal remained green all of the time. Naturally, certain traffic and roadway condition influence saturation flow rate. For example, if the approach is a narrow lane, traffic has to keep a longer gap; if there are large numbers of turning movements and heavy vehicles, the saturation flow rate reduces as well.

Since the saturation flow rate depends on roadway and traffic condition, it is a complicated matter to calculate it, which can vary substantially from one region to another. ImFlow uses the pre-defined saturation flow rate in different time and areas. However, the external conditions might change, so there is a function to estimate the saturation flow rate by real data. As the movements of vehicles in reality cannot fully simulate the idealized condition, the result of this function will be reasonably lower than the actual value.

The function estimates saturation flow rate for each lane controlled by the selected signal group at intersections using real data following the equation,

$$\overline{s} = \frac{1}{N}\sum_{k}^{N} T\frac{m-n}{T_m - T_n}, \tag{3.1}$$

assuming that every vehicle in the queue from first m-to-n is in a stable moving platoon. In Equation 3.1, $\overline{s}$ is the average value of saturation flow, N is the number of vehicles, T is unit time(one hour) in seconds, T_m and T_n are the time when the m-th and n-th vehicles passing through. Taking advantage of the suggestion from HCM (2010), m equals 10 and n is 4 in the traffic queue. Using the approach, average value of observed discharge headway is known.

The algorithm requires real data to satisfy a restriction that traffic is as dense as possible reasonably to pass the intersection in a long traffic flow. Hence, according to some selections, the result returns null because no data satisfy the calculation conditions. As to the plot, x-ticks are the names of detectors associated to the specified signal group, y-axis shows the number of vehicle.

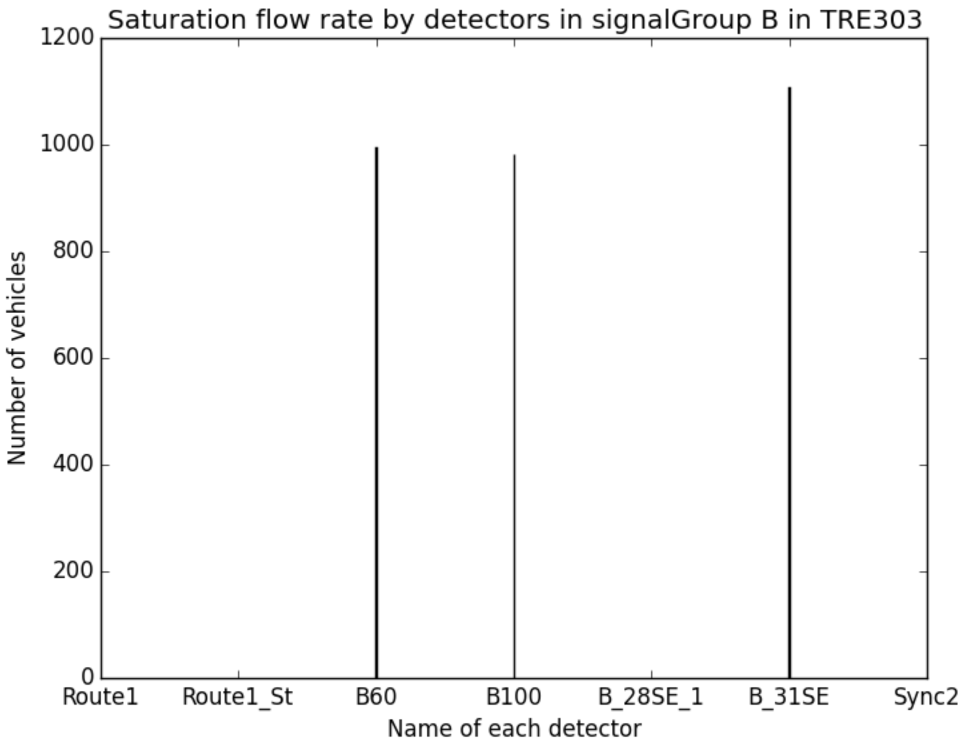


Figure 3.9. Saturation flow rate for sg B at TRE303

Figure 3.9 illustrates saturation flow rate for lanes associated with signal group B at intersection TRE303 in Tampere on 4th, October, 2015. As the image shows, estimated saturation flow rates at the place of detector B60, B100 and B_31SE are available. Since B60 and B100 are located at the same lane, it is reasonable that their values, 996 vphgpl and 983 vphgpl are close, whereas saturation flow rate at detector B_31SE is 1107 vphgpl.

3.3.2 Maximum capacity

Capacity is an adjustment of the saturation flow rate with the real signal green time, as most signals are not allowed to keep an hour continuous green for a certain movement, except the “sleep mode” of major road signals permitting long time green during night time in Finland, if no vehicle requests from minor roads. For instance, if one approach has half an hour green in total per hour, the capacity can be deduced to half of the saturation flow rate in an hour time interval.

Maximum capacity is defined as the maximum number of vehicles that are reasonably expected to traverse a point or a uniform segment of a lane or roadway during a given time period under prevailing roadway, traffic control conditions. The formula to calculate maximum capacity is given as

$$c = (g \div C) \times s, \tag{3.2}$$

where c represents capacity, g is the effective green time for the phase in seconds, C is cycle length in seconds and s is saturation flow rate.

Based on the requirements, capacity can be calculated on different levels, either for each separate lane or lumping the lanes in a direction together. In this application, the calculation of capacity is for single lane by a selected detector in customized time period. It is worth mentioning that critical lane volumes are adequately served, the capacity of that lane should be checked in the same time interval.

The system calculates the total number of vehicles which could pass over the specified detector during the sum of green timing in a certain time period (5 minutes, 10 minutes, and 1 hour etc.). Maximum capacity is positive correlated with saturation flow rate on a lane and green time in a period of a signal group. As to the plot on this measure, the x-coordinate of the green solid diamonds is actual starting time of every time interval, and its y-coordinate indicates the number of vehicles. The dashed line passes through all diamonds by time to show the trend of maximum capacity.

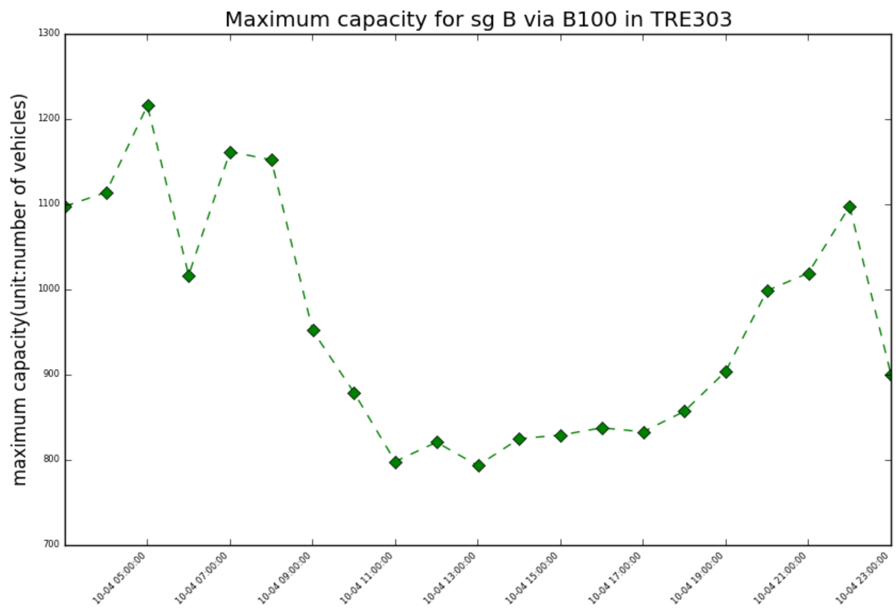


Figure 3.10. Maximum capacity

Figure 3.10 shows maximum capacity of the lane where detector B100 located in one-hour interval at the intersection TRE303 at Tampere during the whole day on 4th, October. As Signal B controls the major approach, the maximum capacity keeps high value over 1000 from midnight to 7:00 am in the morning.

3.4 Volume

Traffic volume estimation means estimating the volume of traffic moving on the roads at a particular point or a uniform segment during a particular time period. Volume of a day or an hour can vary vastly, depending on different days of the week and how busy time of the day is.

Basically, there are two techniques of volume counting at intersections: volumes per detector and volumes per link. In the research, only the former one is used.

This measurement counts that the total number of vehicles could pass over the specified detector on a lane during certain time period (5 minutes, 10 minutes and 1 hour etc.). Two functions support this traffic performance measurement: "Volume on a single direction" and "Volumes by customized multiple directions/detectors".

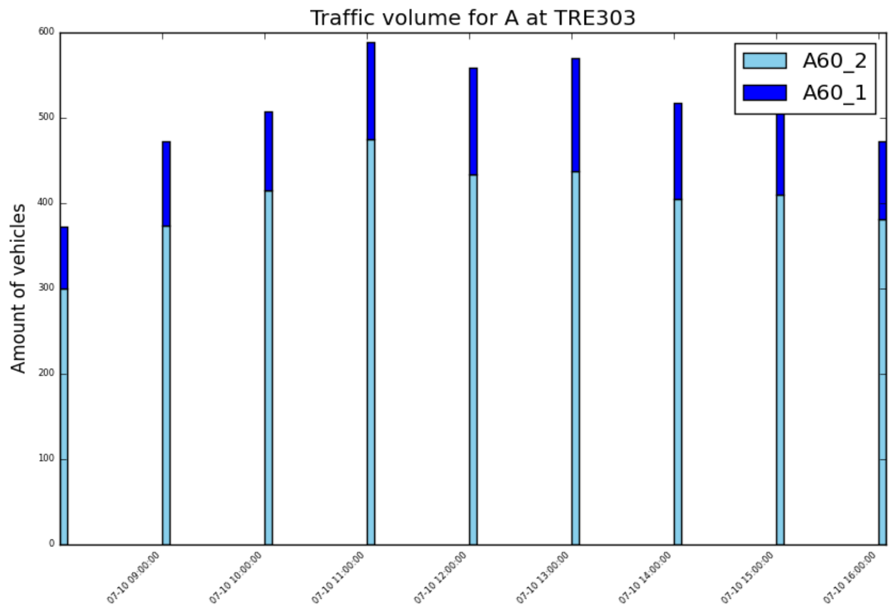


Figure 3.11. Volume on a direction

Volume on a direction

Selecting a loop detector for counting vehicles, if there are more than one lanes paralleling with the selected one on a same direction, the volumes of all the grouped lanes will be calculated and shown as parts of the stacked bars over times like Figure 3.11. The x-coordination of bars is the starting time of intervals and y-axis indicates traffic volume.

Figure 3.11 illustrates the volume on the two lanes controlled by signal group A at the intersection TRE303 on 10th, July from 8:00 am to 17:00 pm in 1-hour interval. The highest volume at that place during that day is from 11:00 am to 12:00 pm with 590 vehicles discharging by the two lanes. This straight lane which is equipped

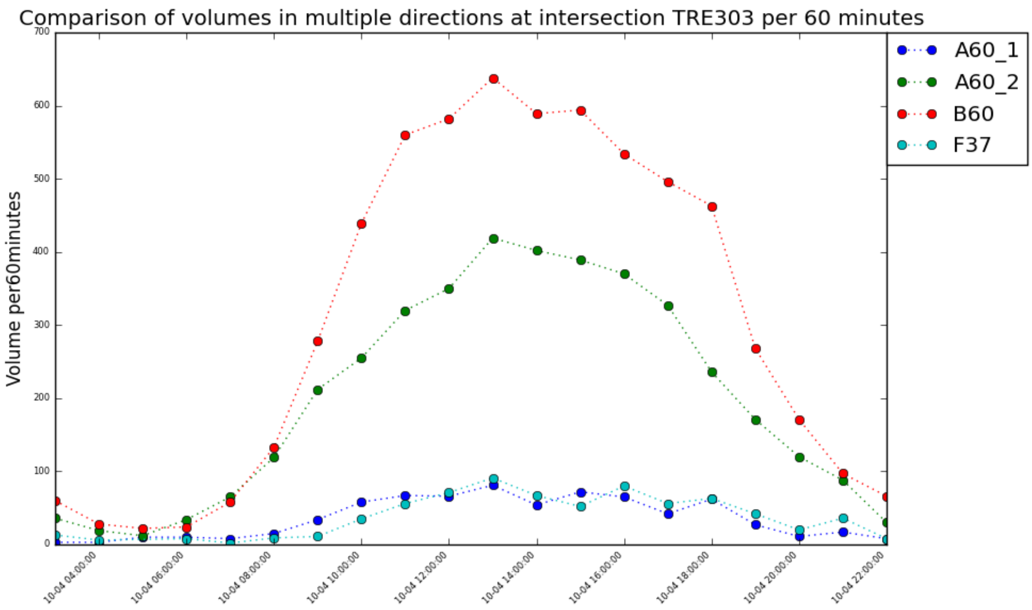


Figure 3.12. Volume on multiple directions

with the detector A60_2 is much busier than the right-turning lane with the detector A60_1 and the result is recorded in Table 3.1.

VOLUME		
Time	A60_1	A60_2
2015-07-10 09:00	73	300
2015-07-10 10:00	99	374
2015-07-10 11:00	93	415
2015-07-10 12:00	114	475
2015-07-10 13:00	125	434
2015-07-10 14:00	132	434
2015-07-10 15:00	113	438
2015-07-10 16:00	107	410

Table 3.1. Volumes at the lanes of signal A at TRE303

Volumes by customized multiple directions/detectors

On the other hand, selecting more than one detectors and comparing the volume flows on multiple directions is allowable for observing and predicting traffic volumes coming from different directions.

Figure 3.12 demonstrates the visualized results on counting volume for a day in every hour at the spots of detector A60_1, A60_2, B60, F37 on the lanes equipped respectively, which gives intuitive comparison of traffic volumes at intersection

TRE303 and is helpful to determine the critical roads and the minor roads, design and adjust the traffic signal timings.

3.5 Arrival on green

3.5.1 Arrival on green percentage

Arrival during green is defined as vehicles in movements arriving at intersection stop bar during green phases and can be calculated as

$$P = \frac{N_g}{(N_g) + (N_r)}, \tag{3.3}$$

where arrival on green is denoted by P, N_g is the number of vehicles arriving during green time and N_r is the number of vehicles arriving during red time.

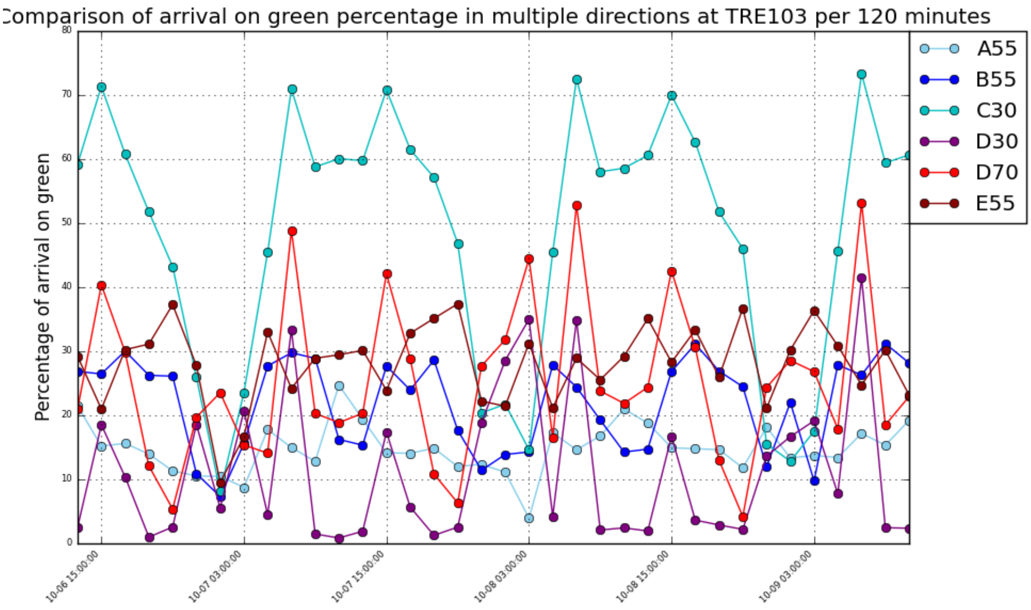


Figure 3.13. Percentage of arrival on green

The traffic number is counted by specified detectors in a time period (5 minutes, 10 minutes and 1 hour etc.). It is a useful traffic metric to evaluate the signal timing performance at individual intersections and deduce the density of traffic flow. Usually, the high percentage of arrival on green is an indicator of smooth traffic.

Figure 3.13 depicts the situation of arrival during green in three days from 12:00, 6th to 12:00 by 2-hour interval, 9th of October at TRE103, one of the busiest intersections located nearby Tampere railway station. It can be seen from the figure that arrival on green in a single direction is roughly repetitive over times.

Taking the volume calculated using C30 as an instance, in every day, the two peak values of arrival during green reaching 70% occur in the same periods: 8:00 am to 10:00 and 16:00 to 18:00 while during the quiet time of every day between midnight 12:00 am to 6:00 am, the value remains lower than 30%. It implies that the controlling of signal timing is pretty effective to this lane holding largest volume in day time.

Similar trend occurs on the directions where D30 and D70 are. As for the situation on the other three detectors A55, B55 and E55, they are more fluctuated in a smaller range, but the overall trend conforms that during day time, the percentage that vehicles arriving at this intersection is higher.

3.5.2 Arrival on green ratio

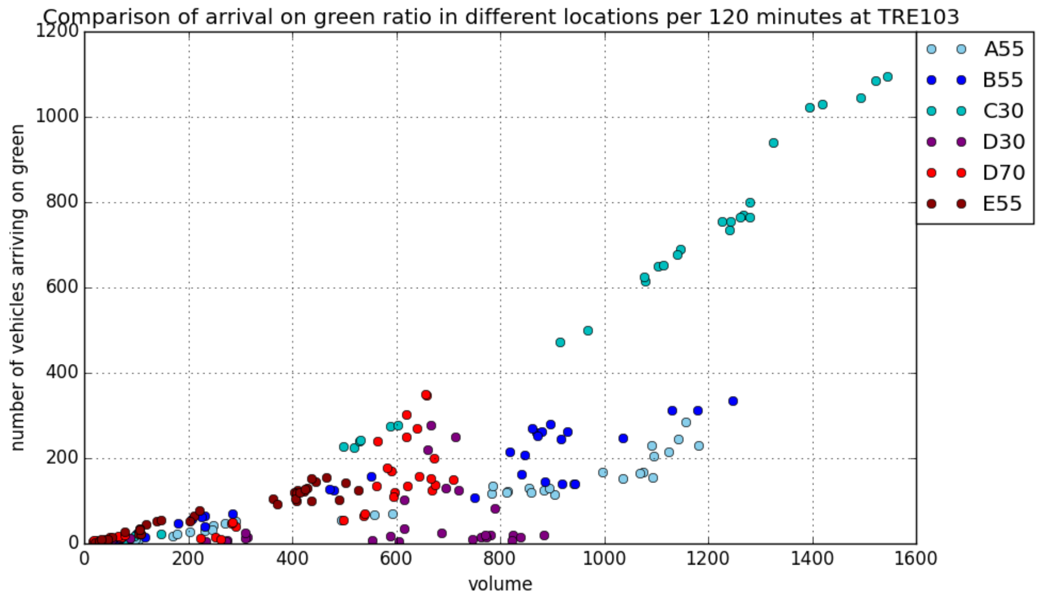


Figure 3.14. Ratio of number of arrival on green and volume

Arrival during green is defined as vehicles arriving at intersection stop bar during green time. The ratio is another measurement from different dimensions related to arrival during green to reveal the issue.

The ratio of arrival during green is used to mine the relation between volume and arrival on green performance. As shown in Figure 3.14, it compares the number of vehicles arriving during green with the total volume under the same prerequisite with Figure 3.13.

In Figure 3.14, the scatter points are clustered by their colors representing the detectors. The most outstanding cluster is from detector C30 with both higher total volume and number of arrival during green. With the total volume of more than 600, it has much more vehicles arriving during green time than others. Comparatively, the direction of detector E55 holds least vehicles, D30 has the lowest value of arrival on green, and A55 and B55 are in the middle class.

Figure 3.15 specifically depicts this performance for detector C30. The linear regression is for modelling the relationship between volume and number of arrival

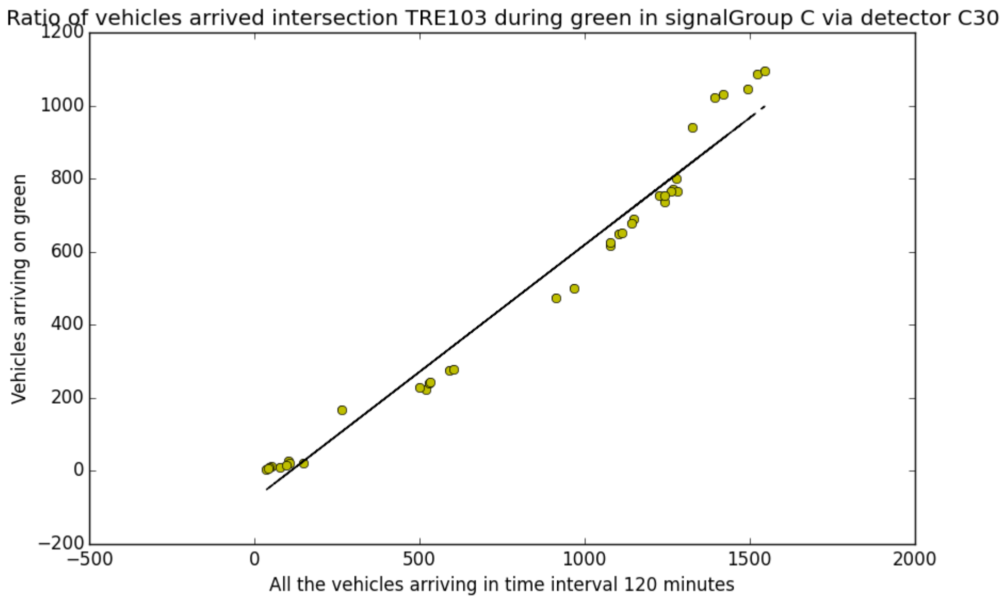


Figure 3.15. Ratio of arrival on green by C33 at TRE103 with linear regression

on green. The slope of the regression line is 0.6, which means the average percentage of arrival on green at detector C30 is 60%, whereas the slopes for A55, B55, D70 are 0.15, 0.25 and 0.25 respectively.

4 Validation and analysis

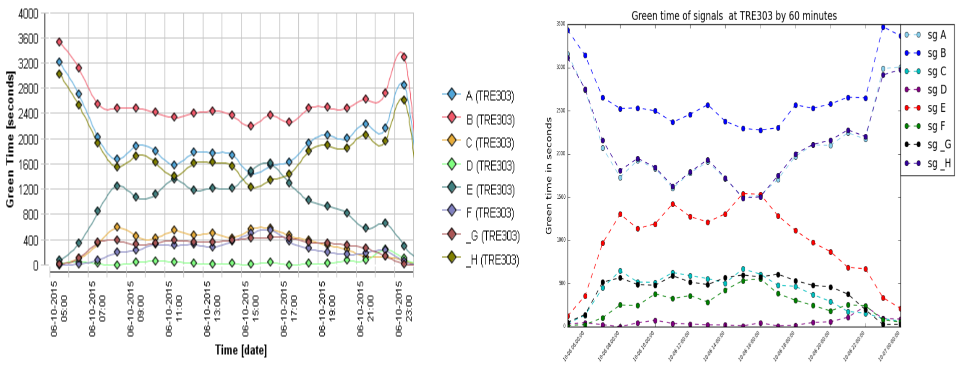
Performance qualification is very important to verify accuracy of measurements and efficiency of algorithms. Comparison with traffic performance reports created by ImFlow on some level to verify and evaluate efficiency of those models is a critical approach in this chapter. Three measurements are compared with results on ImFlow, including green duration, traffic volume and saturation flow rate. As for others measurements, they will be researched according to case studies and specific investigations.

4.1 Validation of results

4.1.1 Comparison on green duration

In the previous chapter, measurements of signal green timing were introduced in some aspects. Besides the two mentioned measurements: green duration in seconds per phase and the percentage of green duration per phase, the cumulative value of green timing in a specified period is also a good measurement of traffic performance, which is also provided by ImFlow.

Therefore, in order to verify the accuracy of measurements for green timing, we will take advantage of this same traffic performance measured by ImFlow.



(a) green time on ImFlow (b) green time

Figure 4.1. Comparison for green timing calculated by two sources

Figure 4.1 demonstrates the two original plots for the cumulative green time in seconds from 5:00 to 24:00 on 6th, October, 2015 at the intersection TRE303 in an hour interval. The left plot is created by ImFlow, one of the released productions by Imtech traffic. And the right plot is the result rendered by the traffic signal analysis tool.

With comparison of the two plots, the trend of two curve lines representing the green duration are consistent. It proves that the calculation of green timing by the

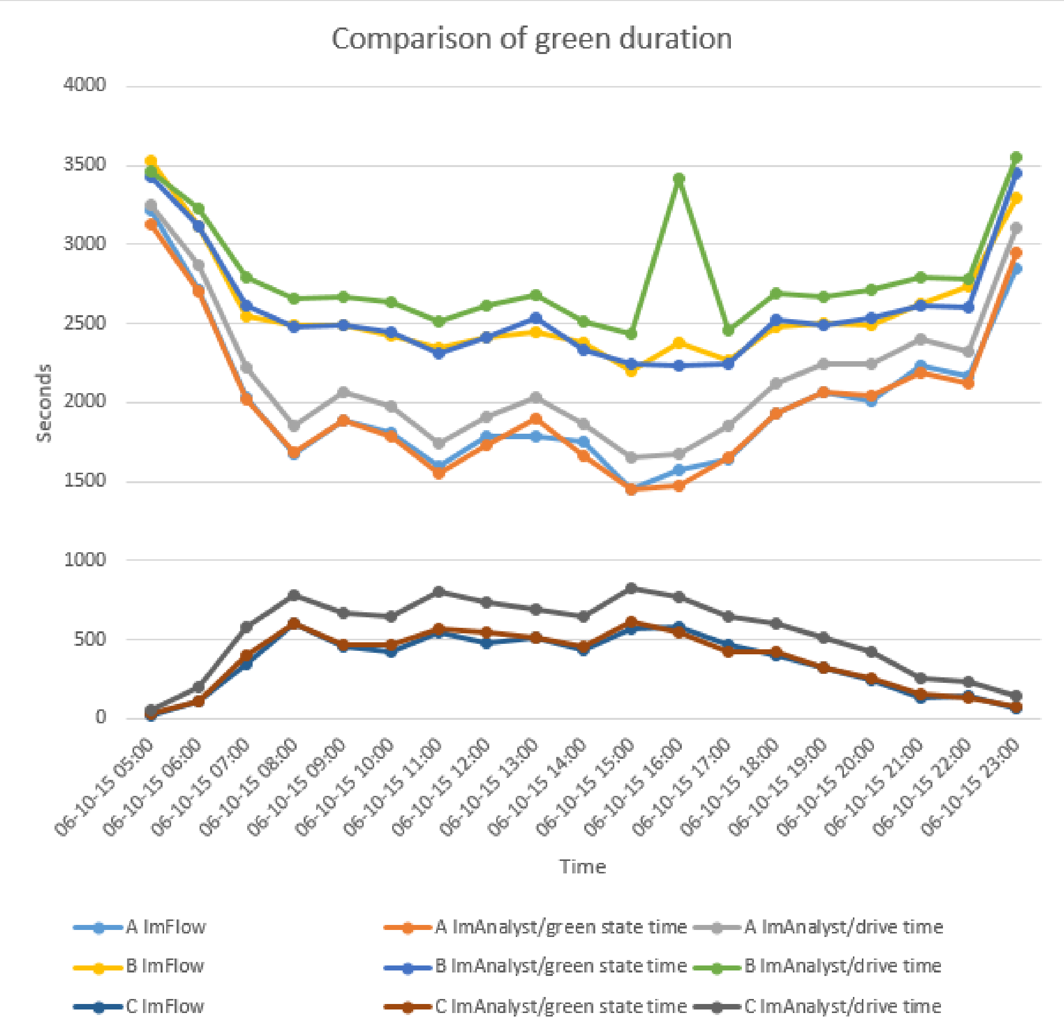


Figure 4.2. comparison of green duration calculated by two sources

application is reasonable and able to simulate the real signal timing on certain level, while the slight difference of values between the two plots still exists. Thus, Table 4.1 extracts Signal group A in the time range of 05:00 and 16:00 of that day, as an instance to compare the values calculated by the analysis tool and ImFlow on details.

One row in Table 4.1 describes that in one-hour time period with the start time specified in first column, the pair of green timings are recorded by the two sources separately. The time difference between the two values is calculated and the percentage of overlapping converges to 100%, and the largest deviation 7.68% happens during 14:00 to 15:00.

4.1.2 Comparison on volume

Traffic volume counting per loop detector is another significant indicator of intersection traffic provided by both ImFlow and ImAnalyst.

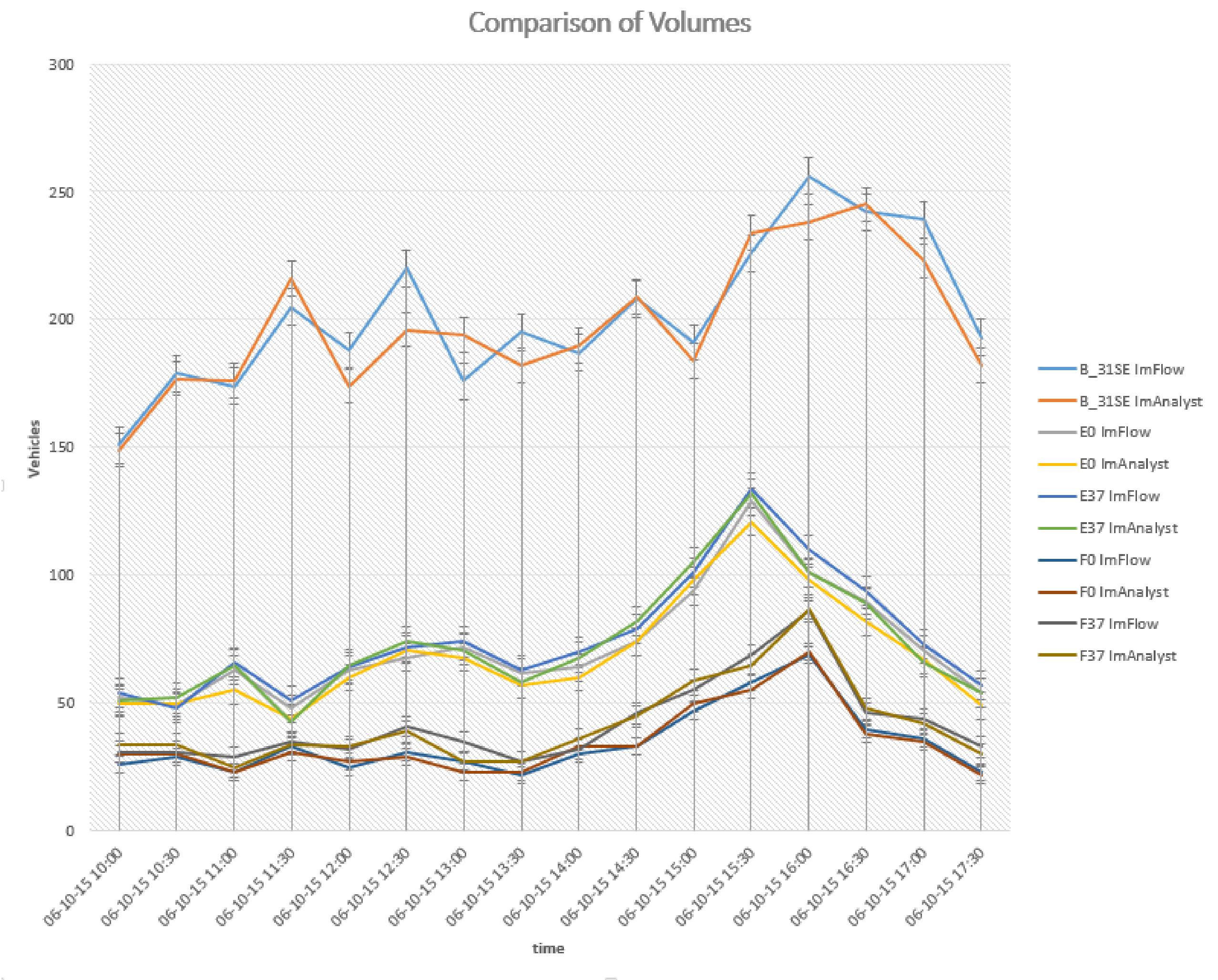


Figure 4.3. Comparison of Volumes calculated by the two systems

Green timing in seconds for signal A					
Start time	ImFlow	Analysis tool	time difference	Overlapping (%)	green percents(%)
2015-10-06 05:00	3214	3131.889	+72.111	102.6	89
2015-10-06 06:00	2709	2699.616	+9.384	100.37	75
2015-10-06 07:00	2031	2022.785	+8.215	100.4	56
2015-10-06 08:00	1677	1687.098	-10.098	99.4	46
2015-10-06 09:00	1888	1882.449	+5.001	100.3	52
2015-10-06 10:00	1805	1787.639	+17.361	101	50
2015-07-10 11:00	1591	1557.597	+33.403	102.2	44
2015-07-10 12:00	1782	1736.25	+45.75	102.56	49
2015-07-10 13:00	1781	1869.110	-77.110	95.3	49
2015-07-10 14:00	1794	1666.384	+127.616	107.68	48
2015-07-10 15:00	1455	1452.086	+2.914	100.2	40
2015-07-10 16:00	1577	1474.004	+102.996	106.98	43

Table 4.1. Comparison the green timing calculated by the two sources

The original plots from the two system with same selection of time span and all other parameters are merged in Figure 4.3, which demonstrates the volumes detected by five detectors used by ImFlow from 10:00 to 18:00 at intersection TRE303 by 30-minutes time interval. Among the detectors, E0 and E37 that are associated with signal E and detectors serving signal F are on the lanes side by side, signal E is right-turning(south-towards-west) and another one is left-turning(south-towards-east). From the graph it is clear that the volumes counted by the detectors on a lane are almost overlapping completely no matter if ImFlow or this traffic analysis tool is being used.

Figure 4.3 presents the result with error bars in both positive and negative directions. It is easily observed the fine distinction between the plots with a table of precise data under the graph. Error bars are a graphical representation of variability of data, and are used to indicate the error or uncertainty in a measurement. They gives a general range of how precise the measurement is. Usually, error bars stand for the standard deviation of uncertainty or standard error or confidence interval. Most error bars for the paired data overlap, the conclusion is that the difference between the mean value of them is not statistically significant.

It is obvious that volumes per detector B_31SE have largest difference and sometime even their error bars are isolated. However, the average difference of paired volumes is only 4 vehicles.

4.1.3 Comparison on saturation flow rate

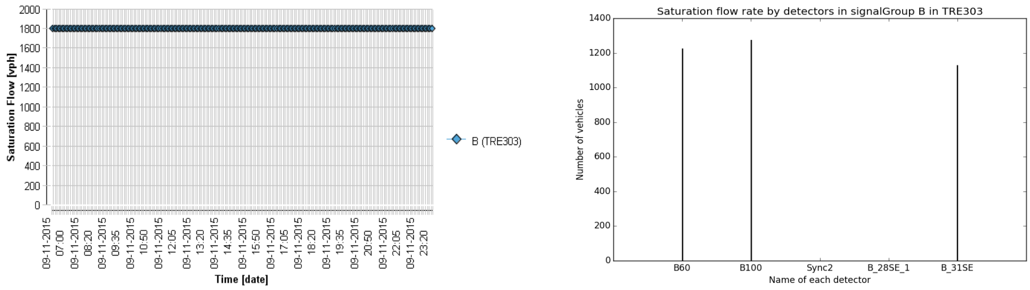
The approach of calculating saturation flow rate on ImAnalyst is to estimate the value using live data. The advantage of this function is reflecting the actual traffic saturation flow rate considering the roadway condition and other environment factors.

Volume at TRE303										
time	B_31SE		E0		E37		F0		F37	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
06-10-15 10:00	151	149	52	50	54	51	26	30	31	34
06-10-15 10:30	179	177	49	50	48	52	29	30	31	34
06-10-15 11:00	174	176	63	55	66	65	23	23	29	25
06-10-15 11:30	205	216	48	44	51	43	33	31	35	34
06-10-15 12:00	188	174	63	60	64	65	25	27	32	33
06-10-15 12:30	220	196	68	71	72	74	31	29	41	39
06-10-15 13:00	176	194	72	68	74	71	27	23	35	27
06-10-15 13:30	195	182	62	57	63	58	22	23	27	27
06-10-15 14:00	187	190	64	60	70	68	30	33	32	36
06-10-15 14:30	208	209	74	74	79	82	33	33	46	45
06-10-15 15:00	191	184	94	98	101	105	47	50	55	59
06-10-15 15:30	226	234	129	121	134	132	58	55	69	65
06-10-15 16:00	256	238	101	98	110	101	69	70	86	87
06-10-15 16:30	242	245	90	82	94	89	40	38	46	48
06-10-15 17:00	239	223	71	67	73	66	36	35	44	42
06-10-15 17:30	193	182	54	49	57	54	23	22	33	30
total	3230	3169	1154	1104	1210	1176	552	552	672	665
average diff	4.07		3.33		2.27		0		0.47	

Table 4.2. Comparison volumes calculated by two sources

The drawback of this approach is that easily lead to underestimation using live data to simulate idea data.

Figure 4.4(b) is saturation flow rate for signal B at TRE303 on 6th, Nov, 2015. The estimation calculated via B60, B100, B_31SE is 1224, 1274, 1130 in terms of passenger car units (pcu) respectively. However, saturation flow rate for signal B on ImFlow is always 1800 as in Figure 4.4(a). It is quite common to assume an ideal saturation flow rate and adjust it for prevailing conditions using adjustment factors like ImFlow does. The study provides a new aspect to verify and test the value for a specific case using live data without any adjustment for other conditions.



(a) Saturation flow rate provided by ImFlow

(b) Saturation flow rate

Figure 4.4. Queue on the four lanes

The reasons to cause the slight difference on green duration and volume compared with ImFlow are complicated, since the entire system is organized by many separate parts, as Figure 1.2 illustrates. First of all, every status of signals and detectors updates would be synchronous with the local data controller unit. Secondly, according to a serial port communication between thousands of controller units and traffic flow garner system. A stream of data with information of signal, detector state and other associated attributes is being collected on database server. At the Internet level, the requests are sent from front-end by traffic engineers via browser to the back end of service. When the computation using data retrieved from database completes, the content of analysis will render to web pages.

On the first step, data flow recording the status of signals and detectors is collected from numerous and independent traffic signal control units, and packed in data packets with a serial of sequence numbers. Besides, delay of information transmission is also possible to happen but immeasurable in this research. On the other hand, packets missing through the processing of information transmission is uncontrollable. By checking the sequence number of data flow from 6th to 9th of October, loss of packet with one or two sequence numbers, happened about a few hundred times in every day, which certainly could have influence on the analysis. Provided that the configuration and equipment of Imflow and ImAnalyst are unequal, their reaction speed might be different and caused time lagging could effect on the edge of data set with fixed time interval.

However, according to those comparisons of results under same parameters using

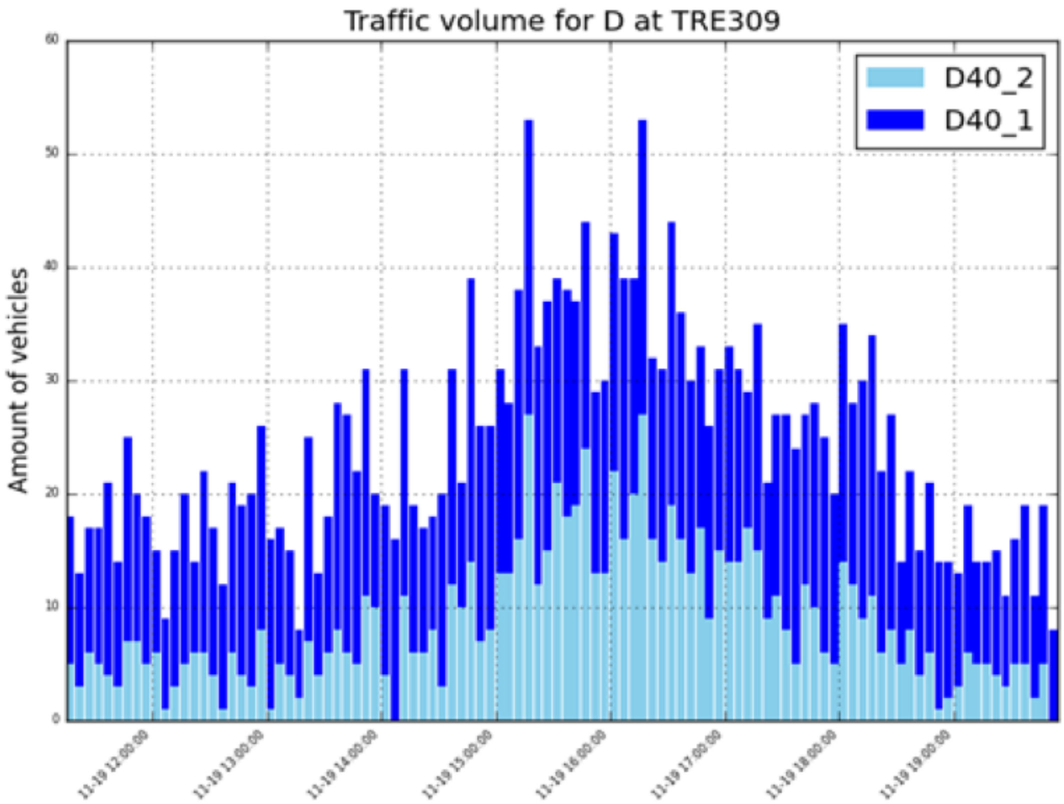


Figure 4.5. Volume by time

ImFlow and ImAnalyst, the changes in the two curves match with small reasonable difference. It proves that ImAnalyst reflects the actual signal timing and the deviation is allowable in industry which have no effect on prediction of traffic capacity and examination of signals operation.

4.2 Analysis of traffic signal measurements

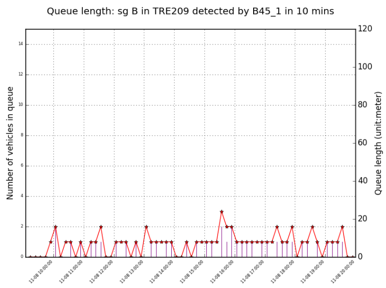
4.2.1 Signal timing plan of operation

The determination of signal timing plans should establish the appropriate basic timing and consider if the signal is coordinated with other nearby signals as a system or operate in isolation (Koonce 2008).

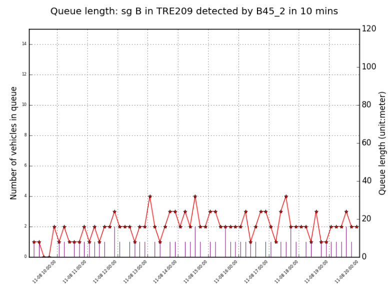
Different plans are used to adapt and adjust traffic on movements in different time. On 19th of November, at 18:00 a new plan replaced the previous plan for rush hour at intersection TRE309. However, as we can see in Figure 4.5, volume on the direction D still remained high in a half hour after 18 pm, even higher than that on rush time on some points. It means that only considering the single direction, the plan changed a little bit earlier than the busy traffic flow discharging on that day and it could be improved. This kind of indicators like traffic volume could be helpful for traffic engineers when inspect signals work and design operation plans.

4.2.2 Green allocation

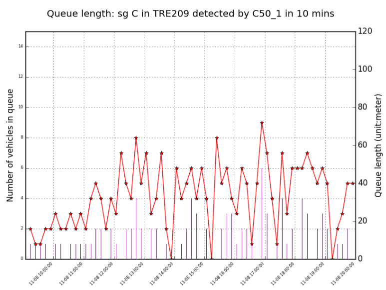
It is also beneficial to improve operational performance and resource allocation with analysis of signal performances measurements. Queue estimation at intersections is a significant indicator of traffic situation. The risk of cycle failure is increased with long-queued vehicles. Subfigure 4.6(a) and 4.6(b) illustrate queue on the direction controlled by signal B at intersection TRE209 from 9:00 to 20:00, while 4.6(c) and 4.6(d) are for signal C. It is deduced that the level of congestion on the lanes of signal C is significantly higher than that of signal B and longer queues generally need more time to discharge. Besides, traffic volumes on the two directions also show that signal C faces more vehicles burden with much shorter green timing (Figure 4.7). The allocation of signal phases is complicated but this kind of unbalance is worth paying attention to and reporting.



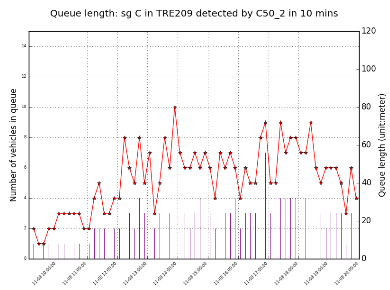
(a) Queue by B45 1



(b) Queue by B45 2

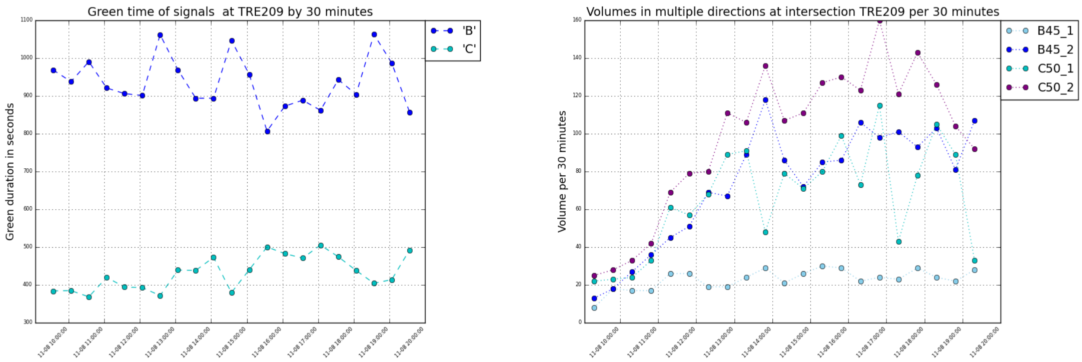


(c) Queue by C50 1



(d) Queue by C50 2

Figure 4.6. Queue on the four lanes



(a) Green duration of signal B and C

(b) Volume of the four lanes

Figure 4.7. Green duration of signal B and C at TRE209

5 Discussion and conclusion

In this research, eight measurements of traffic signal performance are modelled and implemented and their visualized results also are represented. Three measurements of all the experiments are compared with that from ImFlow using same parameters, the professional analysis tool. The compared measurements are volume, green duration and saturation flow rate. The results of comparison for volume and green duration demonstrate that this research gets similar analytical data with ImFlow and the visualized graphs generated by the two tools show same trend. As for saturation flow rate, the result represents considerable difference. The reason to cause the difference is that ImFlow sets pre-defined value of saturation flow rate for every lane, while this research calculates the value using real time data, considering weather, road condition and other environment factors. When traffic is under saturated, the algorithm cannot match well. The web-based application implemented during the research is provided to the traffic engineers in the city of Tampere, for testing the reliability and efficiency of the application and also validating the research. The positive feedback from traffic engineers proves that research is valuable.

In a conclusion, the thesis provides approaches to process and analyze traffic signal data in Finland, implement and visualize measurements of traffic signal performances. An important contribution of the thesis is that provides an economical and lightweight solution to analyze traffic signal data and spreads the service to general intersections. Before that, there is some other business product in the market supporting traffic signal analysis, but it requires construction and installation on roadway and at this moment, only available in several intersections in Tampere.

In Chapter 3, it presents the original approaches and experimental results in detail. In order to verify and evaluate the accuracy of experiments, the first part of Chapter 4 compares a part of experimental results with that mature product, which is currently serving ten intersections in Tampere. The second part of Chapter 4 shows some case analysis in traffic signal research using experimental results. However, as traffic signal performances are complicated, the research is still inadequate and further study and investigation will be carried out in the future. The accuracy of estimation could be improved and more measurements is expected to be implemented, like number of stops. Definitely, there are more possibilities of traffic signal data analysis and further research is worthy of continuing.

6 Acknowledgements

Foremost, I would like to express my deepest gratitude to my supervisor, prof. Jyrki Nummenmaa for the continuous support to my study and research. He provided me the precious opportunity to work in the traffic analysis research group and recommended me to do the interesting and meaningful thesis work at Imtech Traffic & Infra Oy. Those work enhanced my professional skills and gave me financial support. His guidance helps me in all the time of research and writing of the thesis. Without the work experience at traffic analysis research group, it would not be possible to conduct this thesis. I feel so fortunate to be a student of such a prestigious and farsighted professor.

My sincere thanks also go to all my colleagues in Imtech Oy. They always tried their best to help me and answer my questions related to my work. In particular, Mr. Jukka-Pekka Alanissi, my boss and the regional manager of Imtech Oy, who wisely created the project of traffic signal analysis and hired me work for my thesis in the project. And I sincerely thank Mr. Petri Ahola, who is an experienced and skilful software engineer. Petri mentored my work at the company, gave me guidance and insightful comments on programming, also taught me professional knowledge on traffic engineering in Finland patiently. I learned a lot from him about how to be a qualified software developer and knew that programming is hard but fun.

I am also grateful to all the people helped me during my study in University of Tampere, Paula Syrjärinne and Timo Nummenmaa in the traffic analysis research group encouraged and inspired my research at this field. I also thankful to my lab mates, especially Elena Betekhtina, she helped me to enrich my ideas on my research, commented on my views and shared useful information with me. I spent good time with them. I would like to acknowledge all the teachers taught me in UTA, especially Prof. Zhang Zheying for numerous lectures about thesis and good suggestions to me. She is one of the best teachers I have met here and cares every student.

Many friends help me and concern me. I greatly value their friendship and appreciate their belief in me. They brought a lot of happiness and precious memories to me. Once I got in trouble, they always stand on me and support me. My friends helped me move apartments three times, which I cannot imagine how to deal with it by myself; we celebrated every traditional Chinese holiday together and they let me not feel lonely or isolated while studying aboard; they made a fancy double-heart cake and surprised me on my birthday.... They are not only friends, also my families in Finland.

Most importantly, none of this would have been possible without the love and support from my family. The thesis is dedicated to them who give me unconditional and constant love, concern and support all these years. I would like to express my heart-felt gratitude to my parents. And the person who gives me most support is my loving fiancé, Song Ji, who helped me overcome setbacks in the most difficulty time of thesis work, who encourages me to believe and fulfil myself, who accompanies me at every moment of happiness and sadness in the past five years... It would take

days to tell it all. I am certainly imperfect person but I meet the perfect love. I desire to create our future with you.

References

Aljaafreh, A. & Al Oudat, N. (2014), ”Optimized Timing Parameters for Real-Time Adaptive Traffic Signal Controller”, in *Computer Modelling and Simulation (UKSim), 2014 UKSim-AMSS 16th International Conference on*, pp. 244–247.

Anusha, S. P., Vanajakshi, L. D. & Sharma, A. (2013), ”A Simple Method for Estimation of Queue Length”, *International Journal of Innovation Research in Science, Engineering and Technology*.

Ban, X., Herring, R., Hao, P. & Bayen, A. (2009), ”Delay Pattern Estimation for Signalized Intersections Using Sampled Travel Times”, *Transportation Research Record: Journal of the Transportation Research Board*, 2130, 109–119.

Chanloha, P., Usaha, W., Chinrungrueng, J. & Chaodit, A. (2012), ”Performance Comparison between Queueing Theoretical Optimality and Q-Learning Approach for Intersection Traffic Signal Control”, in *Computational Intelligence, Modelling and Simulation (CIMSiM), 2012 Fourth International Conference on*, pp. 172–177.

HCM (2010), *Highway Capacity Manual*, Washington, D.C. : Transportation Research Board, 2010.

Idaho Transportation Department (1995), *IDAHO TRANSPORTATION DEPARTMENT TRAFFIC MANUAL*.

Koonce, P. (2008), ”Traffic Signal Timing Manual”, Available from Internet: `http://www.signaltiming.com/The_Signal_Timing_Manual_08082008.pdf`.

List, G. & Cetin, M. (2004), ”Modeling traffic signal control using Petri nets”, *IEEE Transactions on Intelligent Transportation Systems*, 5, 177–187.

Liu, H. X., Wu, X., Ma, W. & Hu, H. (2009), ”Real-time Queue Length Estimation for Congested Signalized Intersections”, *Transportation Research Part C: Emerging Technologies*, 17, 412 – 427.

Ljubisic, N. (2014), *ImFlow Central User Manual*.

Shao, C.-q. & Liu, X.-m. (2012), ”Estimation of Saturation Flow Rates at Signalized Intersections”, *Discrete Dynamics in Nature and Society*.

Traffic signal wikibook (2015), ”Fundamentals of Transportation Traffic Signals”, Available from Internet: `https://en.wikibooks.org/wiki/Fundamentals_of_Transportation/Traffic_Signals`.

Traffic wave wikipedia (2015), ”Traffic wave”, Available from Internet: `https://en.wikipedia.org/wiki/Traffic_wave`.

Turner, J. & Harahap, G. (1993), ”Simplified Saturation Flow Data Collection Methods”, in *CODATU Vi Conference on the Development and Planning of Urban Transport, Tunis, February 1993.*, pp. 65–76.

United States Department Transportation (2015), ”Federal highway administration”, Available from Internet: `http://ops.fhwa.dot.gov/publications/signal_timing/03.htm`, [Online; accessed 14-Oct-2015].

Webster, F. V. (1958), *Traffic Signal Settings*, London Her Majesty’s Stationery Office.

Wikipedia (2015), ”Signaltiming — Wikipedia, The Free Encyclopedia”, Available from Internet: `https://en.wikipedia.org/wiki/Signal_timing`, [Online; accessed 14-Oct-2015].

Wolfe, M., Monsere, C., Koonce, P. & Bertini, R. (2007), ”Improving Arterial Performance Measurement Using Traffic Signal System Data”, in *Intelligent Transportation Systems Conference, 2007. ITSC 2007. IEEE*, pp. 113–118.